# Occulters for Terrestrial Planet Imaging from Space

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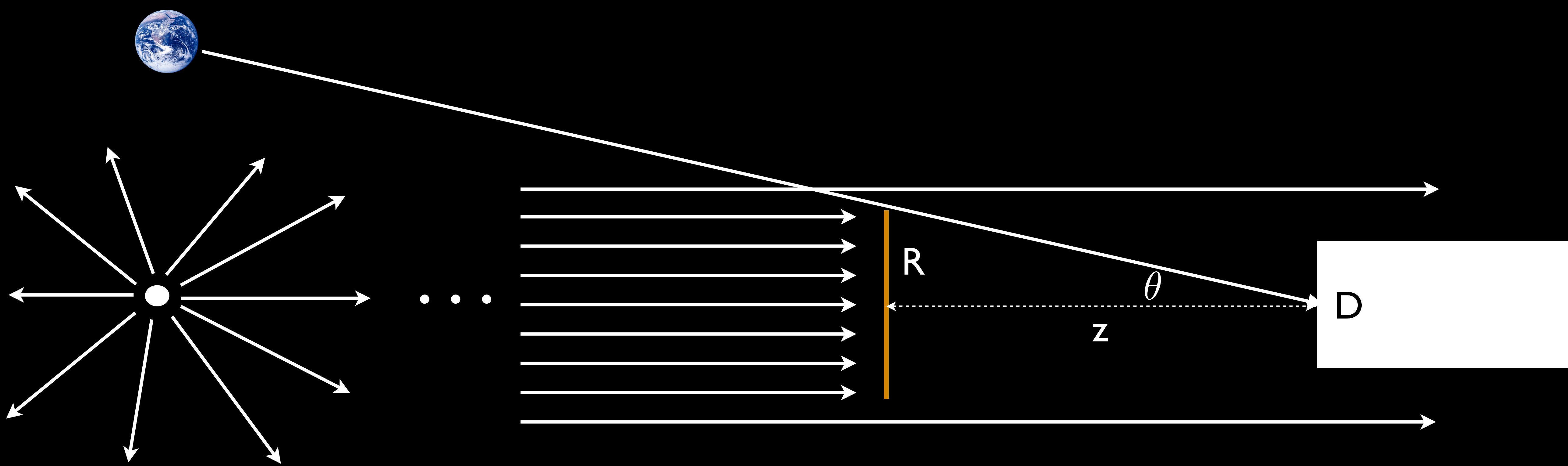
# Outline

- Occulter Design Basics and Advantages
- Potential Missions of Different Scales
- Potential Science Yield & Comparisons
- Technology Challenges and Requirements
- TDEM Mechanical Design (+ movie)
- Technology Roadmap

# Simple Ray Optics Description




Shadow size given by R

Inner Working Angle given by: $\tan\theta = \alpha = \dfrac{R}{z}$

For D = 4 m, R = 3 m, and IWA = 75 mas, z ~ 10,000 km

This demonstrates the fundamental size and distance scale for the starshade.

# What about Diffraction?

Fresnel Number: $$\frac{4R^2}{\lambda z} \sim O(1)$$

Is there a Fraunhofer Regime with sufficient shadow?

Yes! $z >>> R \quad (z \sim 10^{10} R)$ Can be shown using only uncertainty principle.

One solution is putting the occulter very close to the point source with very small inner working angle, which is not very practical.

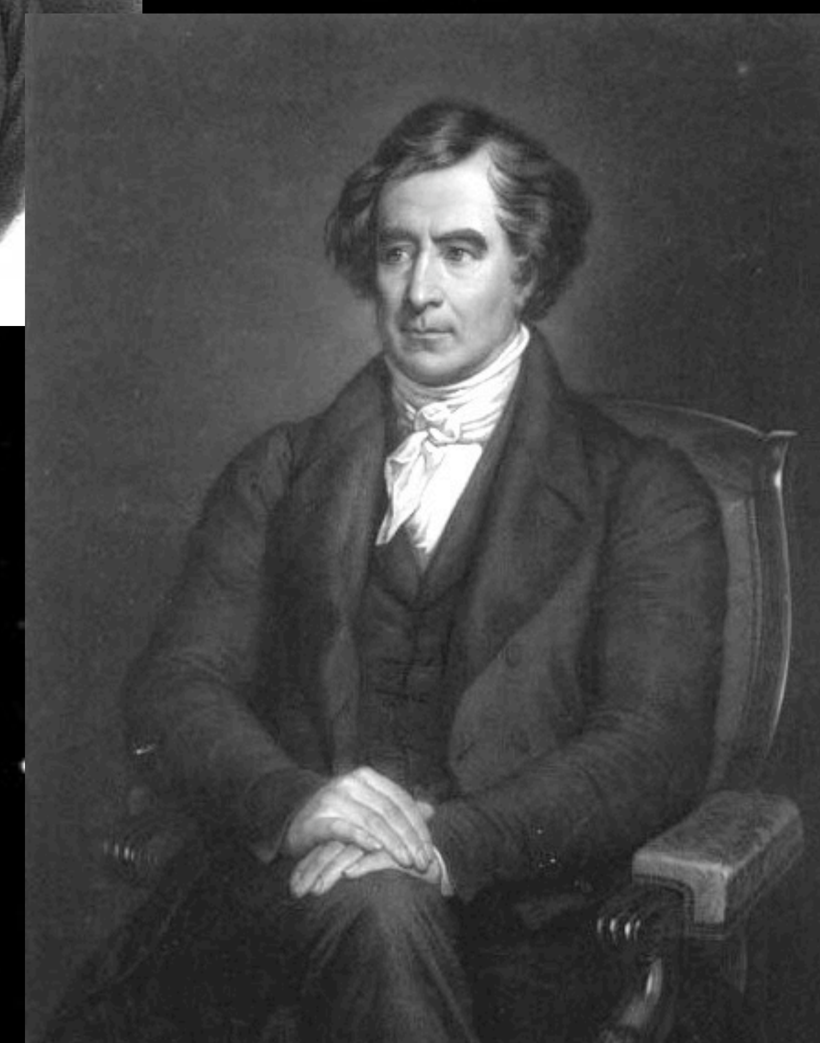
We thus have to work in the Fresnel regime.

Fresnel Diffraction using Babinet's Principle:

$$E(\rho, Z) = E_0 e^{\frac{2\pi i Z}{\lambda}} \left( 1 - \frac{2\pi}{i\lambda Z} \int_0^R A(r) J_0\left(\frac{2\pi r \rho}{\lambda Z}\right) e^{\frac{\pi i}{\lambda Z}(r^2+\rho^2)} r\,dr \right)$$

# For A(r) =1 (Solid Disk) it Doesn’t Work

Poisson didn’t believe the wave theory of light. He pointed out that light falling on a circular object would have a bright spot at the center of its shadow.

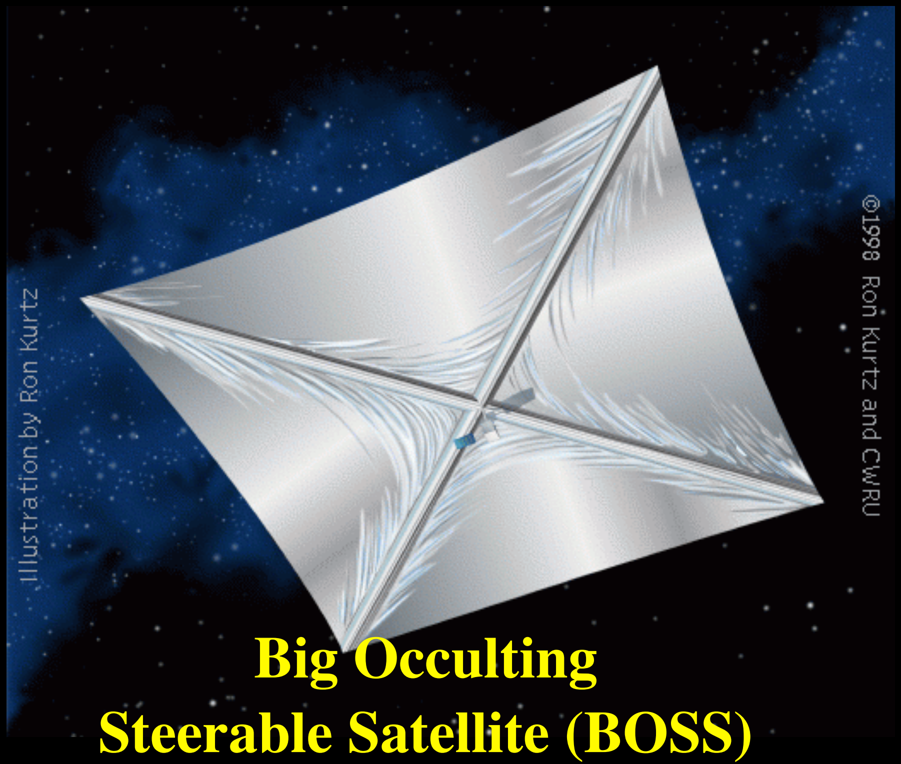


Arago did the experiment.

Poisson was wrong.

# Apodized Occulters (A(r) ≤ 1)

It has been known since 1962 (Spitzer) that an apodized occulter can produce the needed shadow.




Copi & Starkman (2000)


Schultz (2003)

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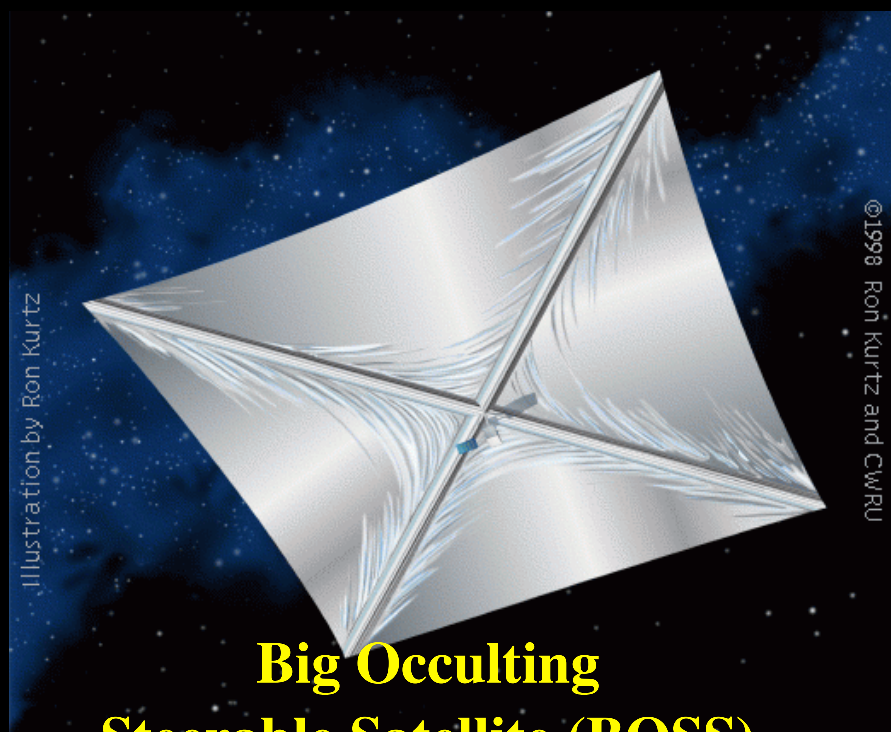



**Big Occulting Steerable Satellite (BOSS)**

Copi & Starkman (2000)

**UMBRAS**

Schultz (2003)

## How is A(x) practically found?

# Semi-Analytical Approach

Copi & Starkman (2000) and Cash (2006) solved for the electric field at center of telescope (rho = 0):

$$E(0,z) = E_0 e^{\frac{2\pi i z}{\lambda}} \left( 1 + 2\pi i \int_0^{\sqrt{\frac{\alpha R}{\lambda}}} A(u) e^{\pi i u^2} u du \right)$$

It is now possible to find closed form of integral in terms of elementary functions. Copi & Starkman integrated with A(r) in terms of Chebychev Polynomials. Cash approximated limit by infinity and integrated with A(r) a Hypergaussian.

The parameters of A(r) are selected to produce very high contrast at center. Occulter size and remaining parameters tuned numerically to achieve desired contrast across shadow and bandwidth.

# Optimal Apodizer Design

Solve linear program to find apodization at discrete points along radius.

Fix inner working angle, occulter radius and petal length and then minimize suppression in shadow subject to constraints on:

* Electric field
* Shadow diameter
* Shortest wavelength of bandpass
* Longest wavelength of bandpass
* Smoothness
* Engineering features (gaps and tips)

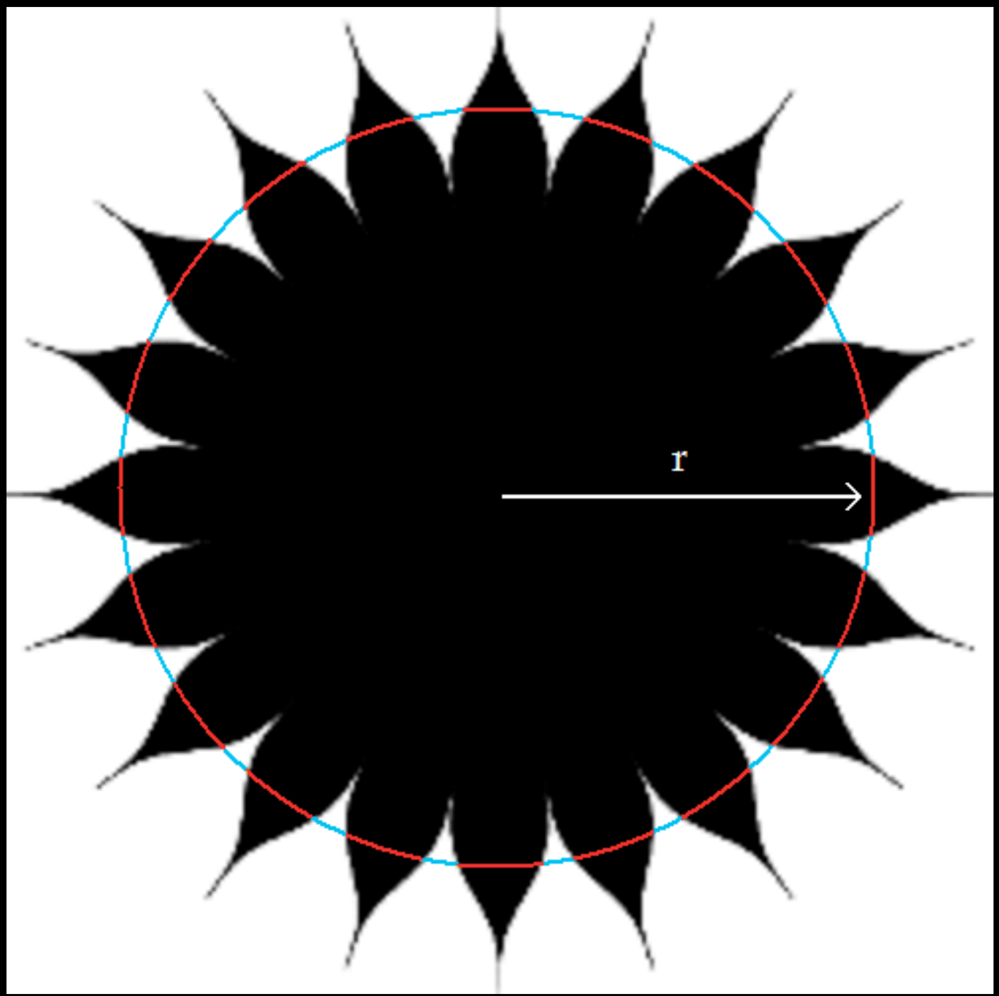
→ Global minimum establishes size, distance, and petal shape of occulter

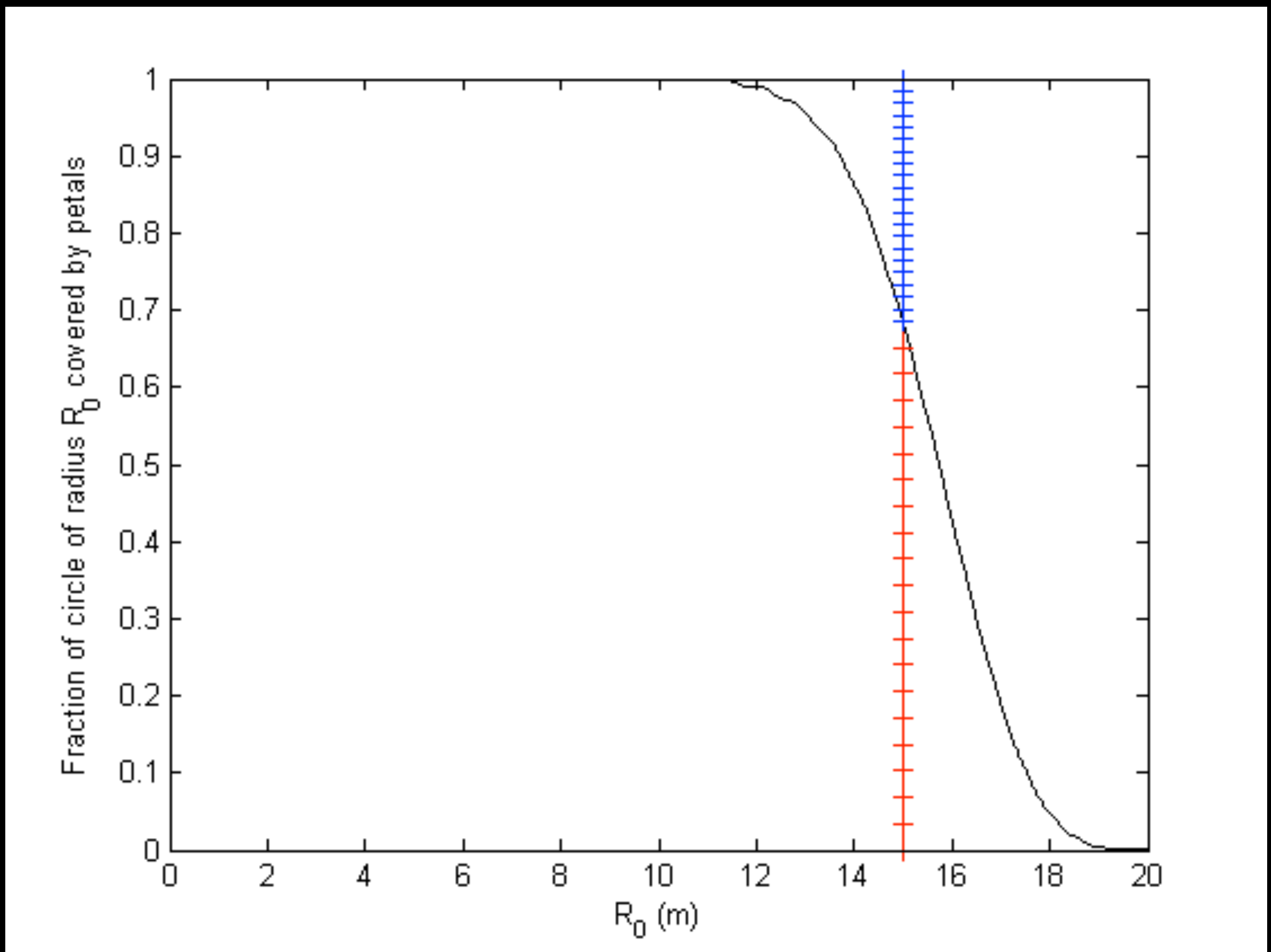
The increased degrees of freedom allow for smaller occulter design and flexibility to achieve constraints such as larger gaps or wider tips.

# Convert apodization to binary occulter

Uses same approach as star-shaped pupil design.

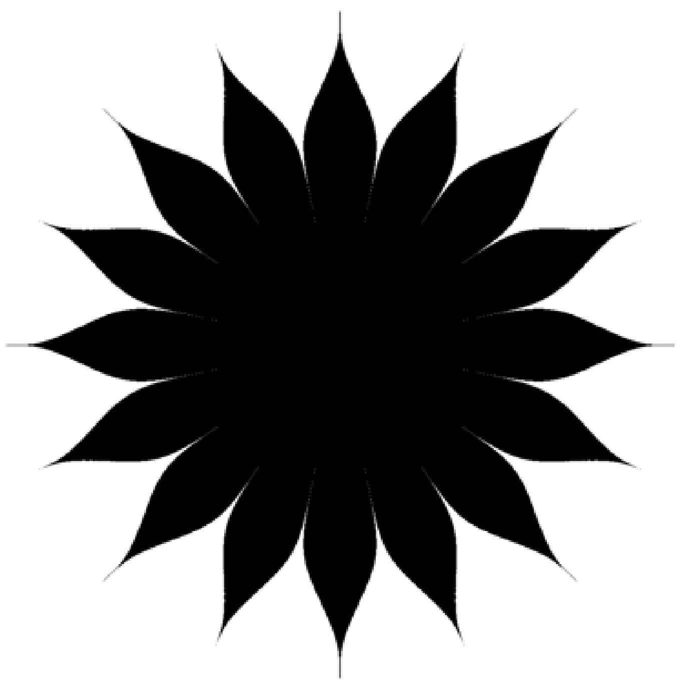
Marchal (1985), Simmons (2005), Cash (2006), Vanderbei et al. (2007)

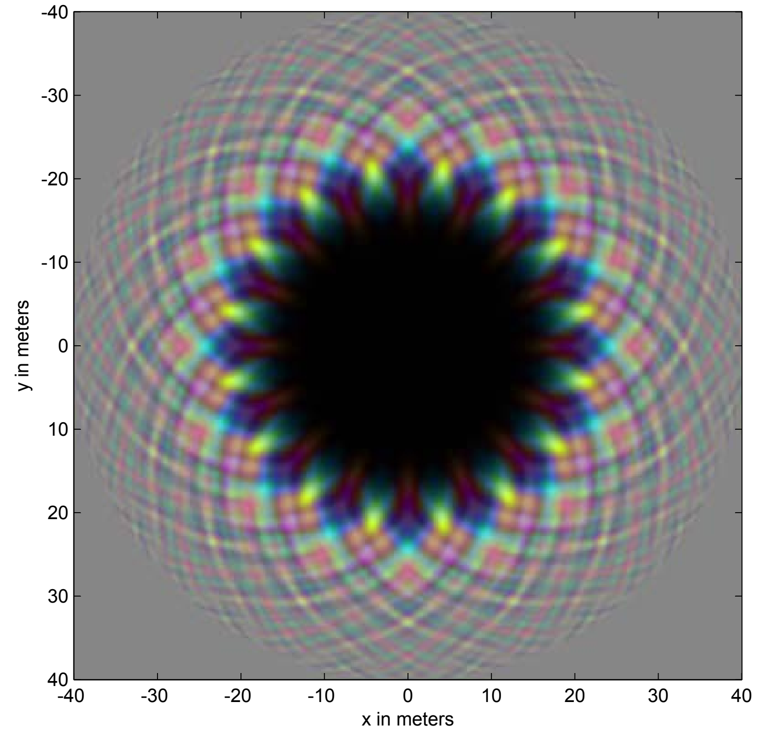


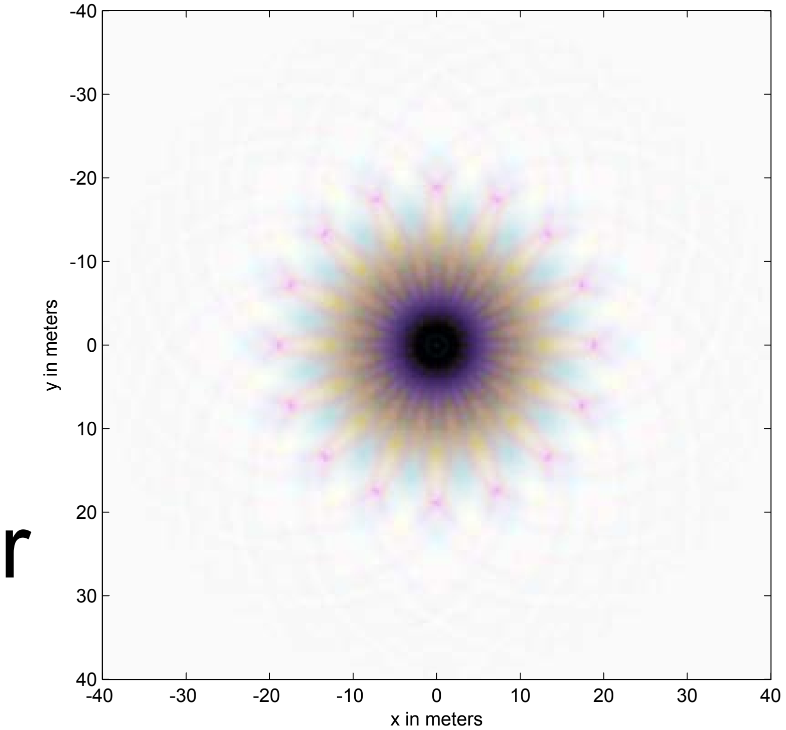



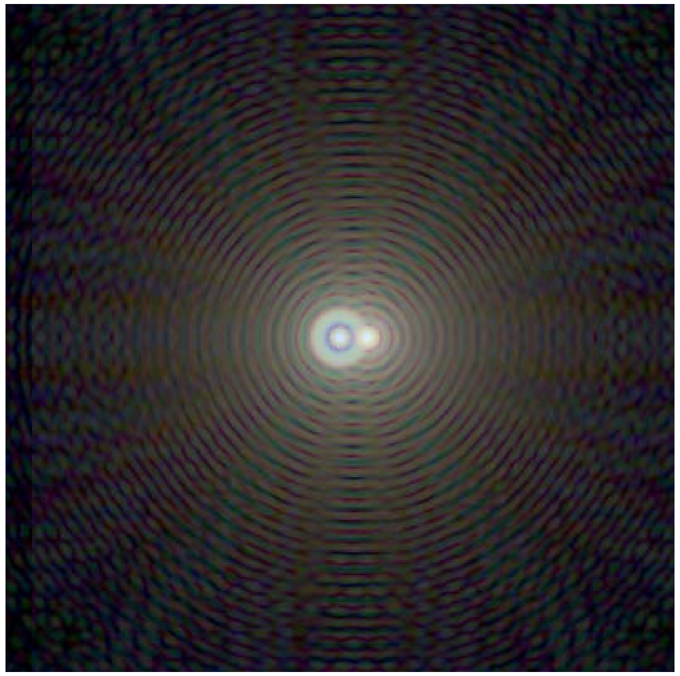

$$
\begin{aligned}
E_{o,\text{petal}}(\rho,\phi) &= E_{o,\text{apod}}(\rho) \\
&\quad - E_0 e^{\frac{2\pi i z}{\lambda}} \sum_{j=1}^{\infty} \frac{2\pi(-1)^j}{i\lambda z} \left( \int_0^R e^{\frac{\pi i}{\lambda z}(r^2+\rho^2)} J_{jN}\left(\frac{2\pi r\rho}{\lambda z}\right) \frac{\sin(j\pi A(r))}{j\pi} r\,dr \right) \\
&\quad \times \left(2\cos\left(jN(\phi-\pi/2)\right)\right)
\end{aligned}
$$

# Shaped Occulter





Note: Shadow designed for $10^{-12}$ contrast to allow for errors.

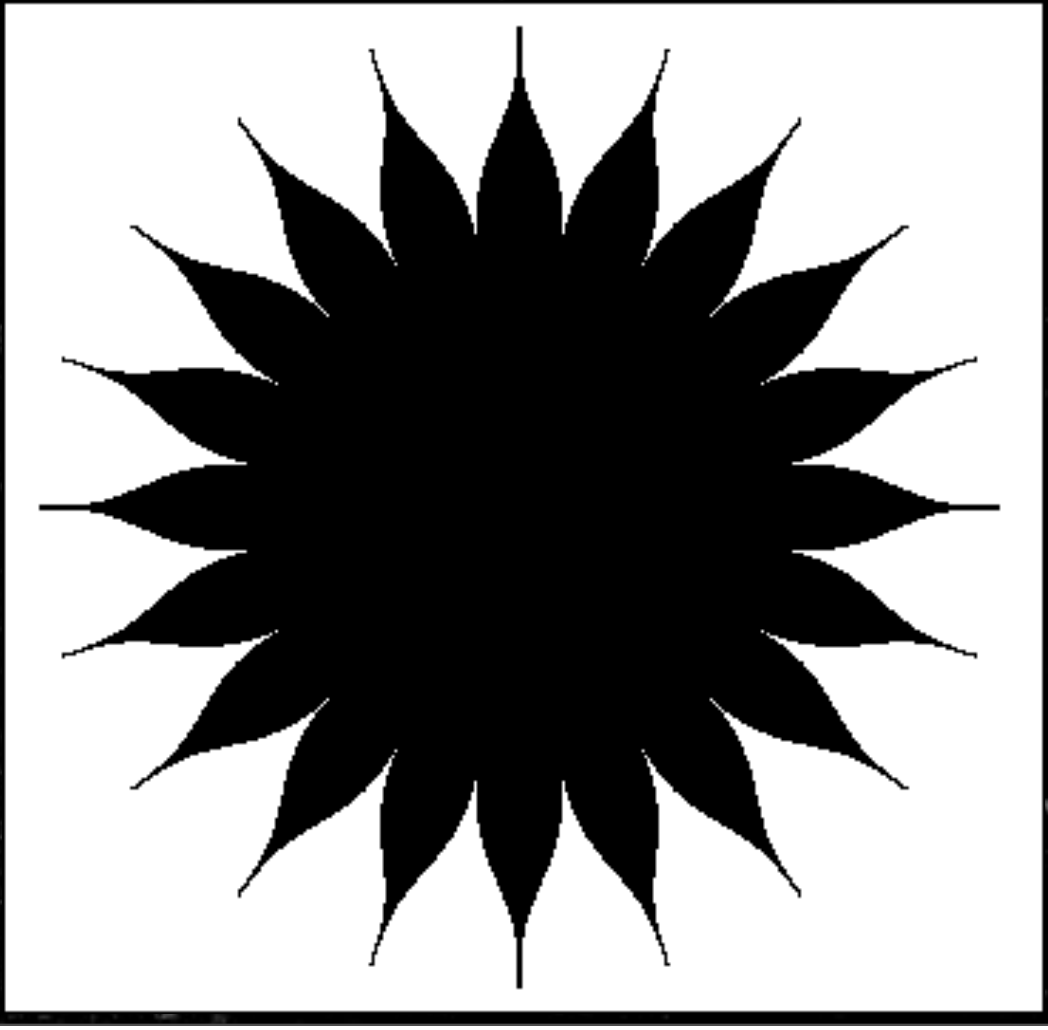
# Two Distance Occulters

We can take advantage of Fresnel number invariance to narrow the bandwidth and design a smaller occulter with shorter petals operating at two distances.

$$z \to z/a \quad \lambda \to \lambda a$$

$$E(\rho, Z) = E_0 e^{\frac{2\pi i Z}{\lambda}} \left(1 - \frac{2\pi}{i\lambda Z}\int_0^R A(r) J_0\left(\frac{2\pi r \rho}{\lambda Z}\right) e^{\frac{\pi i}{\lambda Z}(r^2+\rho^2)} r\,dr\right)$$

51.2 m, 20 m petals,
0.12 mm gap, 1.6 mm tip

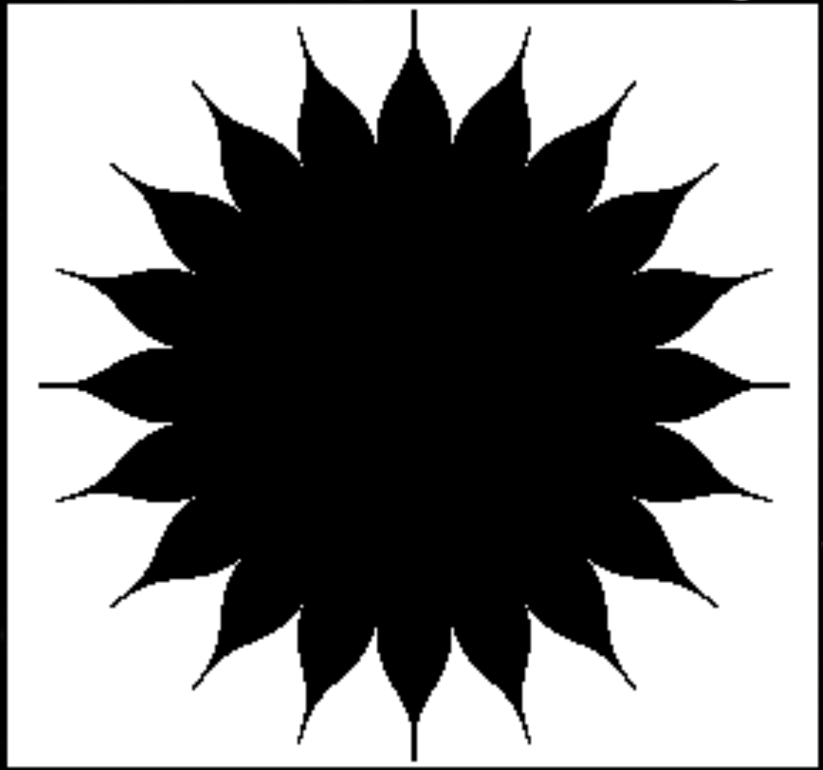


40 m, 10 m petals, 1 mm gap, 1 mm tip

*To scale:*

*Left:* single distance occulter

*Right:* two-distance occulter



Optimal designs for a 4 meter telescope with 75 mas IWA and 250-1000 nm bandpass

# What are Starshade advantages?

- No wavefront control, relaxed stability requirements on telescope, conventional on-axis design
- Very wide spectral band (only way to get UV without dramatic improvements in coatings)
- Inner working angle largely independent of size of telescope and wavelength.
- High throughput (2 - 4 times higher than coronagraphs)
- Large discovery space (no dark hole, unlimited outer working angle, 360 degree imaging)
- Robust general astrophysics during slews

## Inner Working Angle Comparisons (450-900 nm)

| | Occulter (250-550, 500-1100 nm) | 2 l/D Coronagraph | 3 l/D Coronagraph | 4 l/D Coronagraph |
|---|---|---|---|---|
| 4 m Telescope | 75 (150) mas | 47-93 mas | 70-140 mas | 94-186 mas |
| 1.5 m Telescope | 75 (150) mas | 125-248 mas | 187-372 mas | 250-496 mas |
| 1.1 m Telescope | 90 (180) mas | 170-347 mas | 255-520 mas | 340-694 mas |

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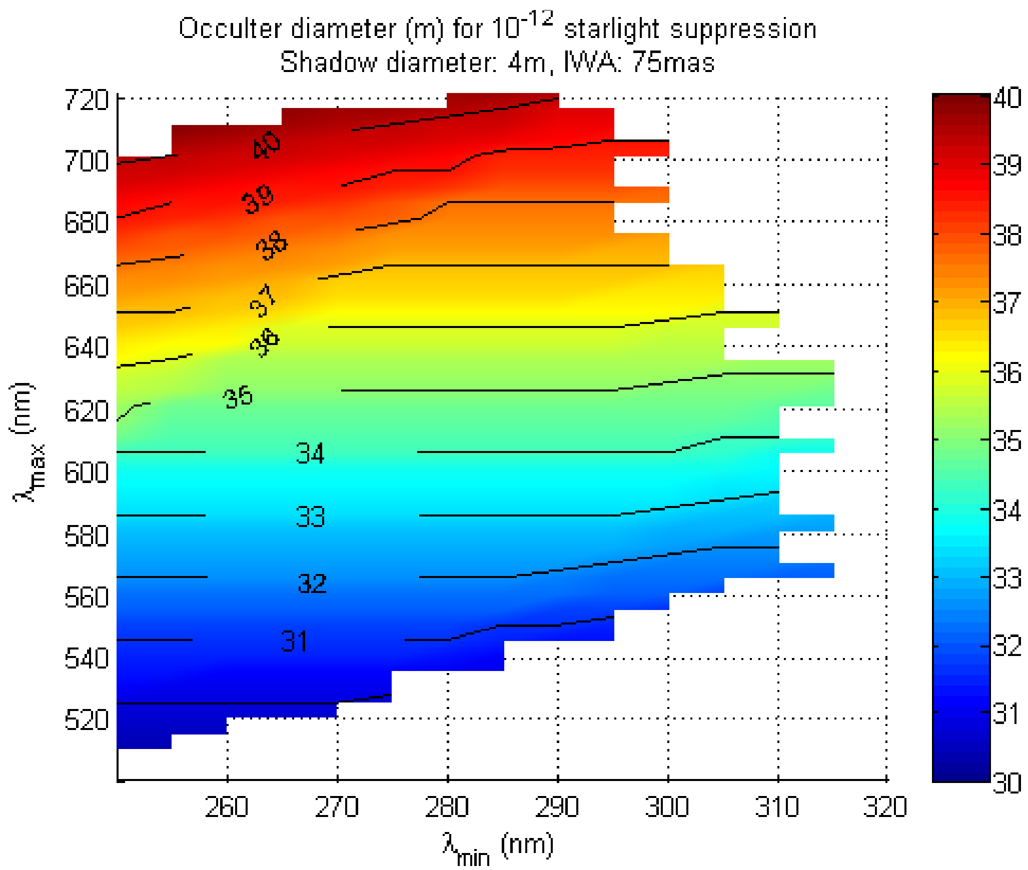
**But there are challenges (coming up)**

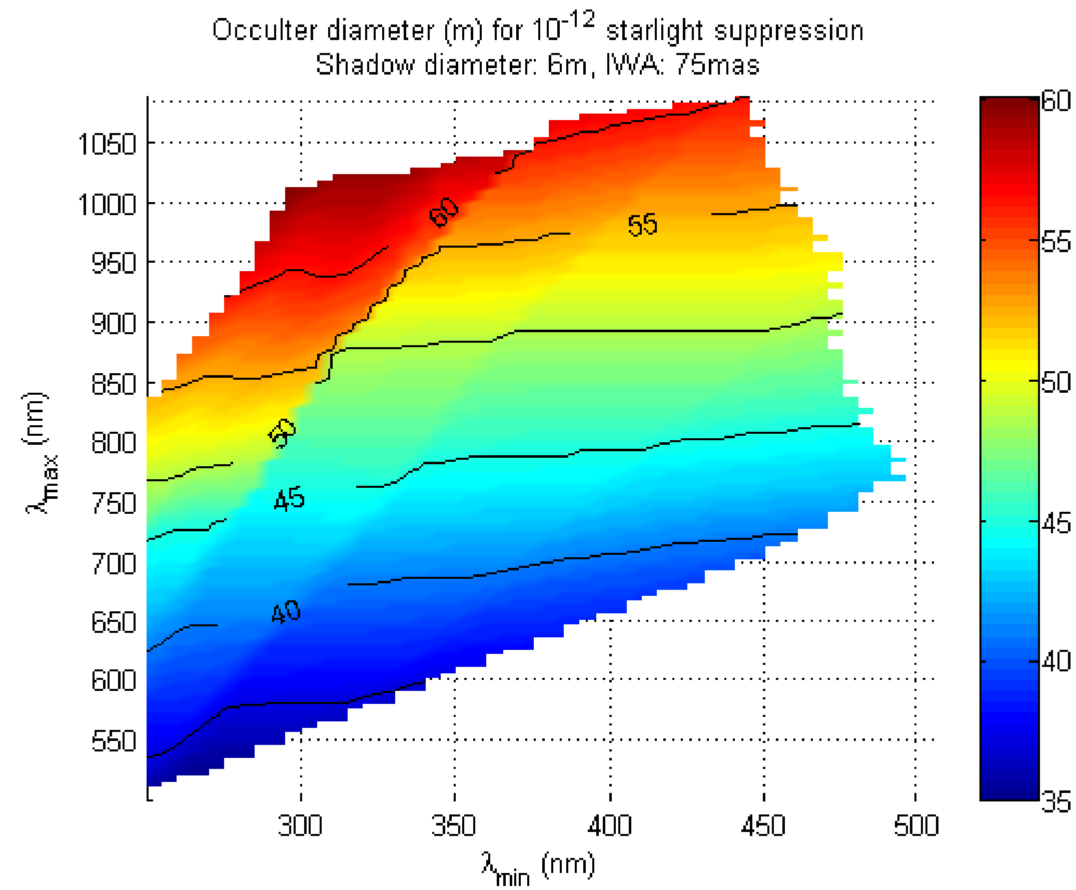
# Sample Missions at Different Scales

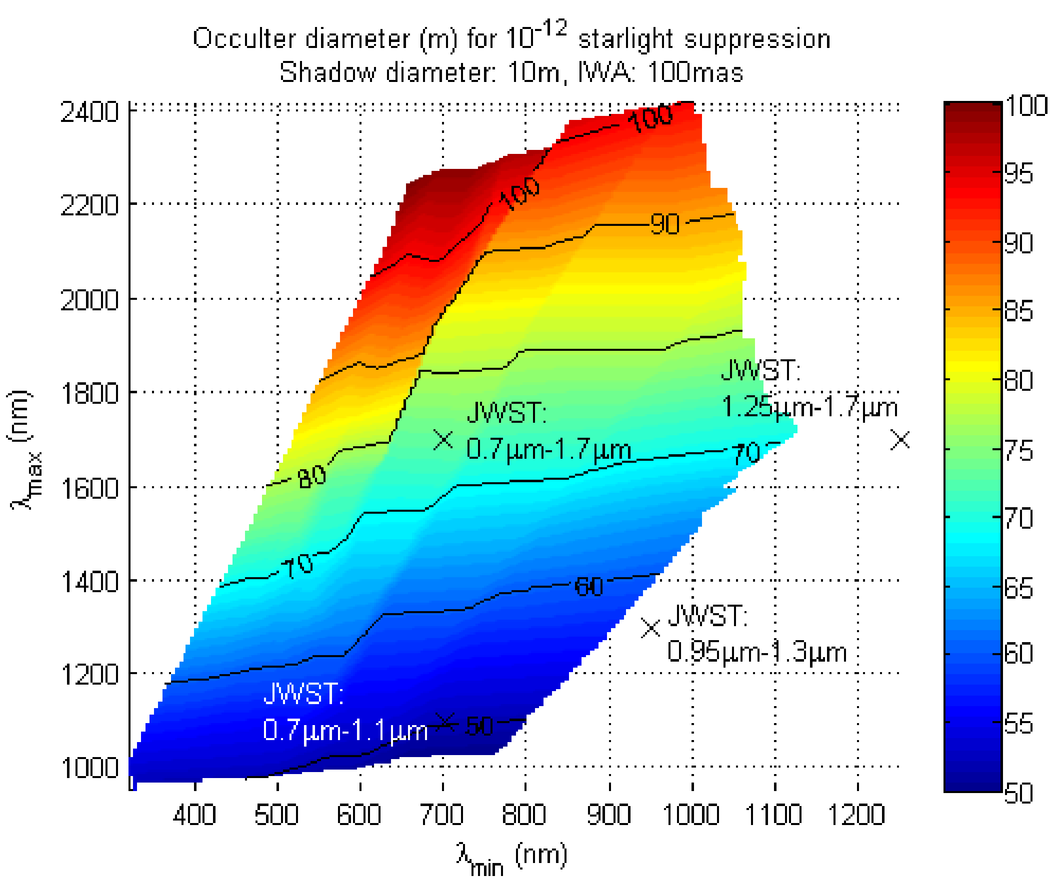
- Large Missions (> 8 m telescopes)
- 4 m flagship telescope
- Small to Medium Telescopes (< 2 m)
- Occulters with JWST

# Occulter Scaling

(Cady et al. 2011)



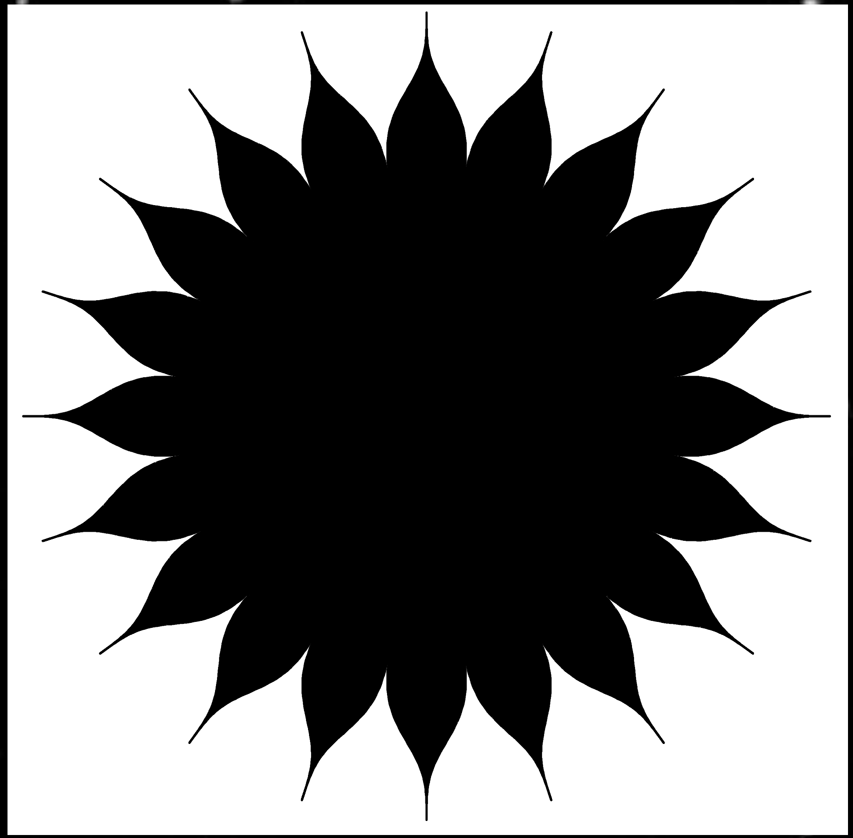



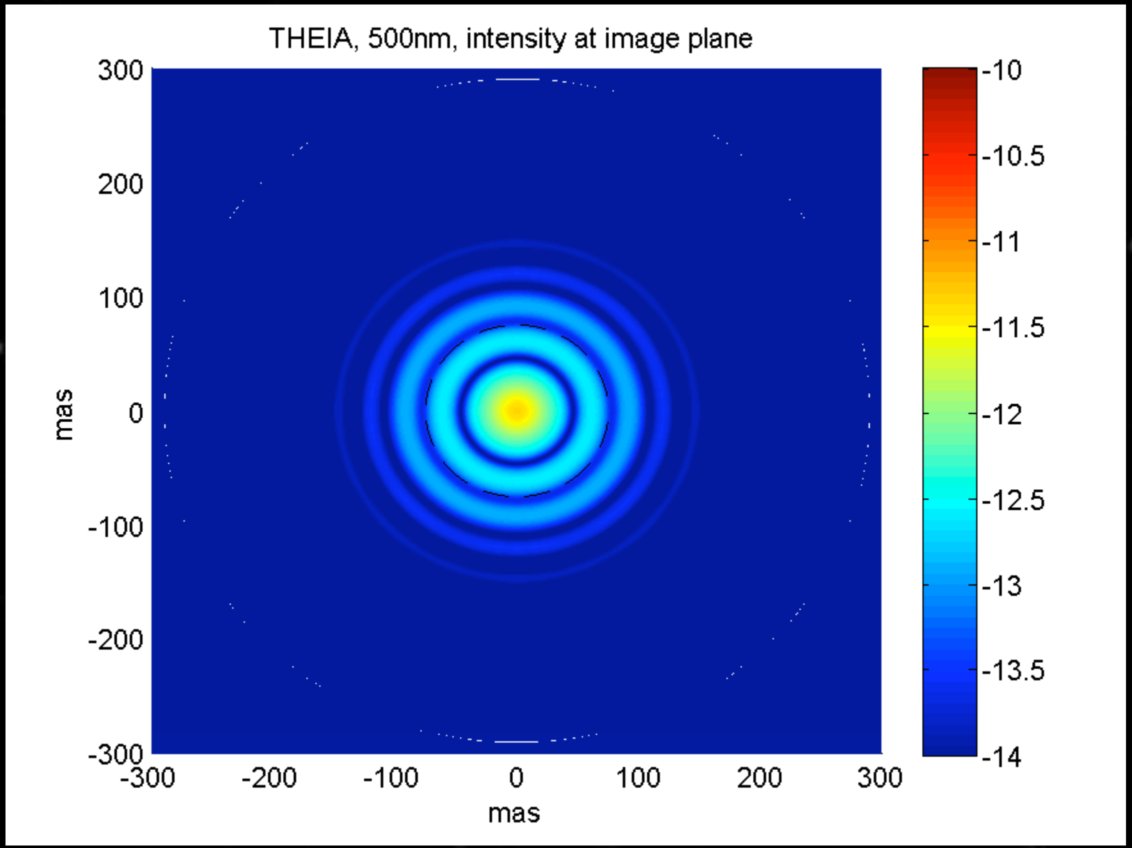

Occulter diameters as function of wavelength band for three different shadow sizes and inner working angles.

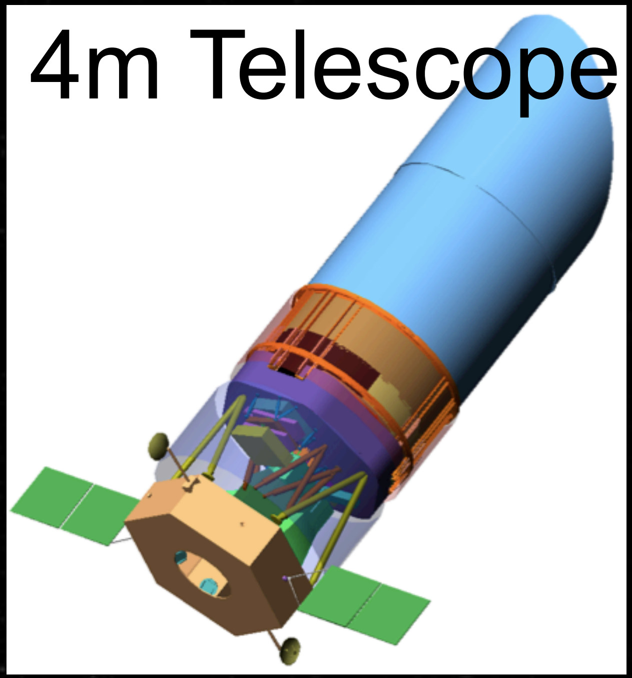
- 4 m shadow, 75 mas IWA
- 6 m shadow, 75 mas IWA
- 10 m shadow, 100 mas IWA

# THEIA Occulter

2009 Astrophysics Mission Concept Study (Princeton)





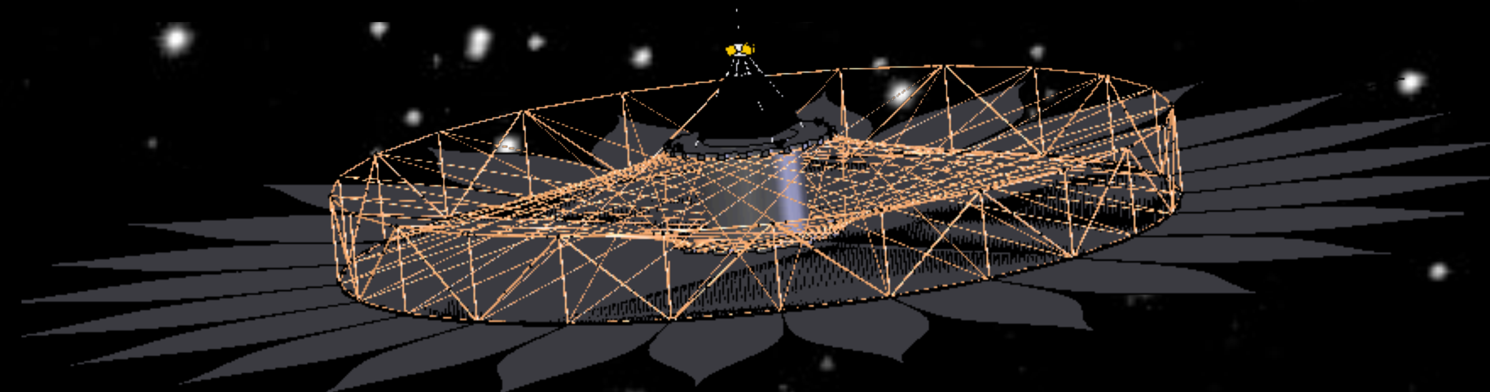




Two Distance Occulter (55,000 km max)

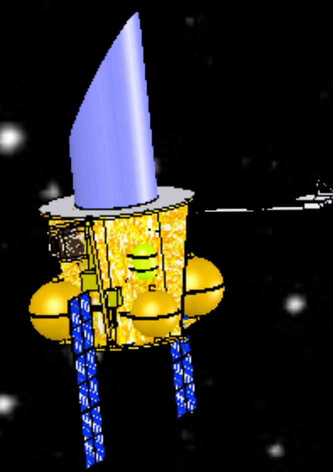
40 m diameter,
10 m petals,
1 mm gap,
1 mm tip

Bands:
250-550 nm (75 mas)
500-1100 nm (150 mas)

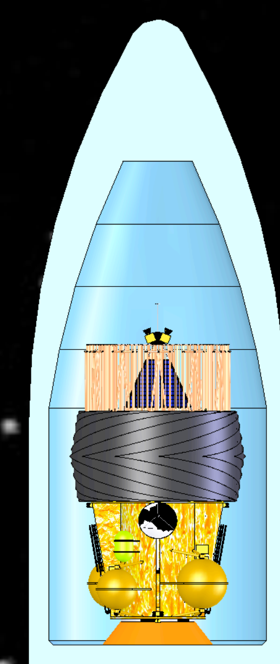
# Moderate Telescope + Occulter

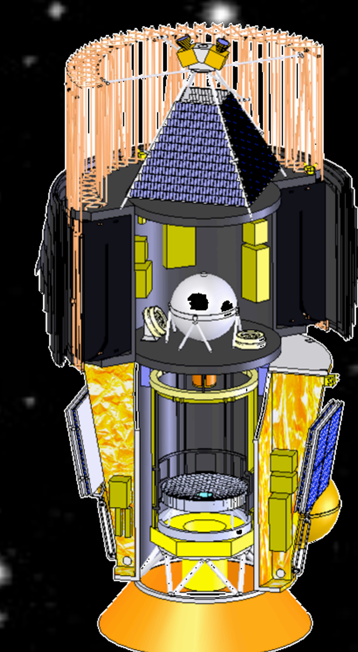


- 1.1 -1.5 meter
  (diffraction limited at 0.3 - 0.5 microns)
- Advantages:
  - Lightweight relatively inexpensive telescope can move, acquire occulter and stationkeep using chemical propulsion
  - Same resolving power as JWST
  - Can use smaller occulter (~ 30 m) with relaxed requirements.
  - Can detect up to 5 Earths with eta = 0.3
  - Can repeat visits for orbits
  - Can detect ozone
  - Opportunities for general astrophysics

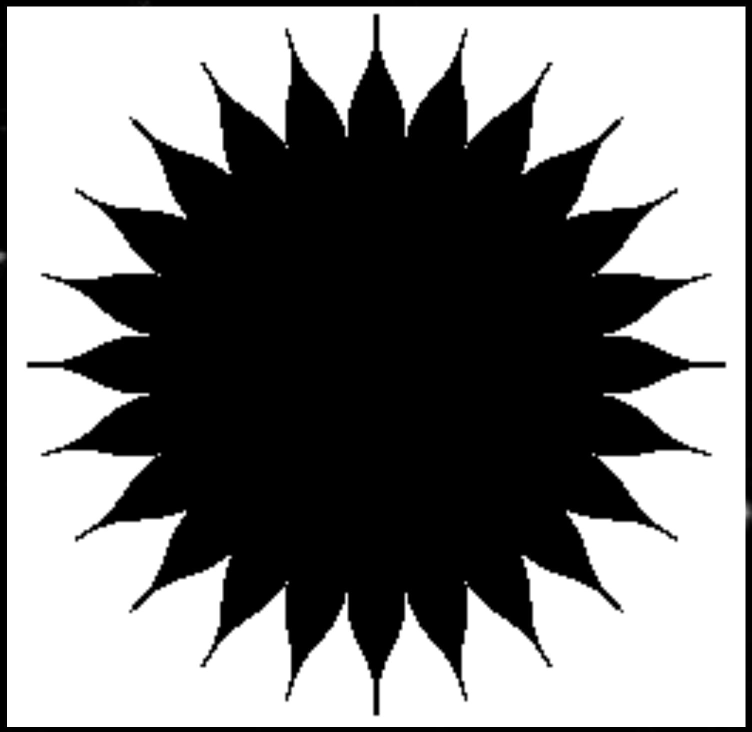


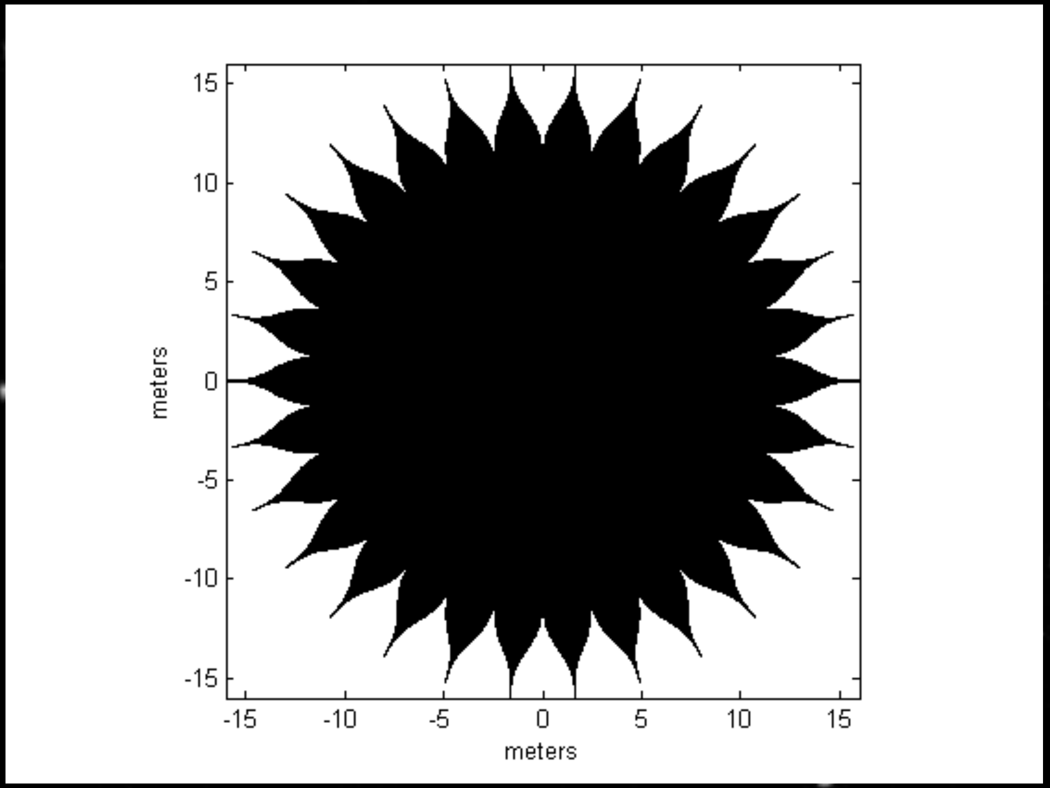
$O_3$





# Small Telescope Occulters



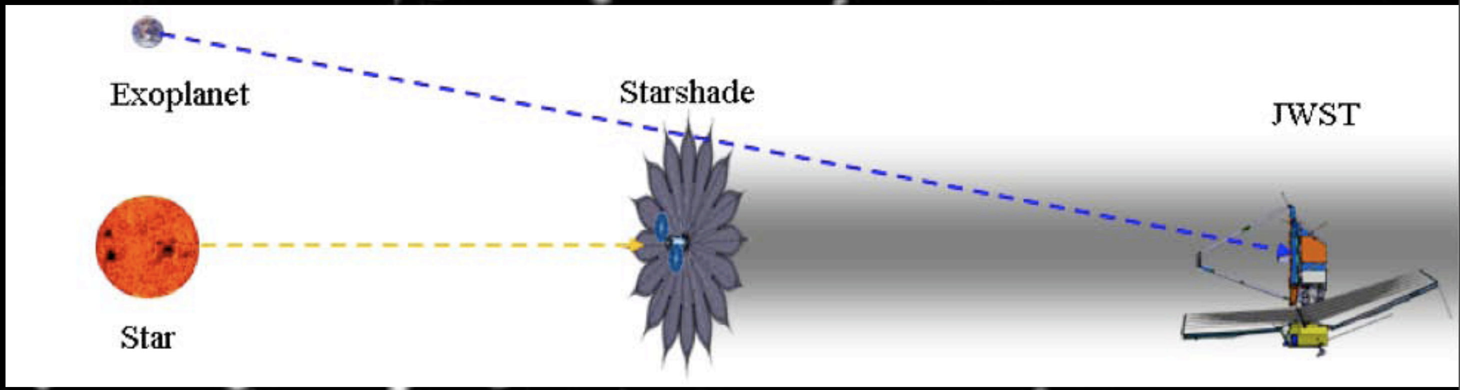



<u>O3 Occulter:</u>
30 m diameter,
75 mas IWA
7.25 m petals,
1.1 m telescope

<u>DI22 Occulter:</u>
32 m diameter,
90 mas IWA
6 m petals,
1.5 m telescope

# Occulter with JWST

- 6 m telescope (10 m shadow)
- NIRCam for detection
- NIRSpec for characterization
- Limited field of regard (tilted occulter)
- Non-spinning
- Diffraction limited at 2 μm
- Requires new camera design and laser beacon for position sensing




<u>Wide Band (700-1700 nm)</u>

75 m occulter
19.5 m petals
100 mas IWA (77,000 km)
~0.1 mm gaps and tips
Upgraded NIRSpec filters

(Soummer et al. 2010)

<u>Narrow Band (950-1300 nm)</u>

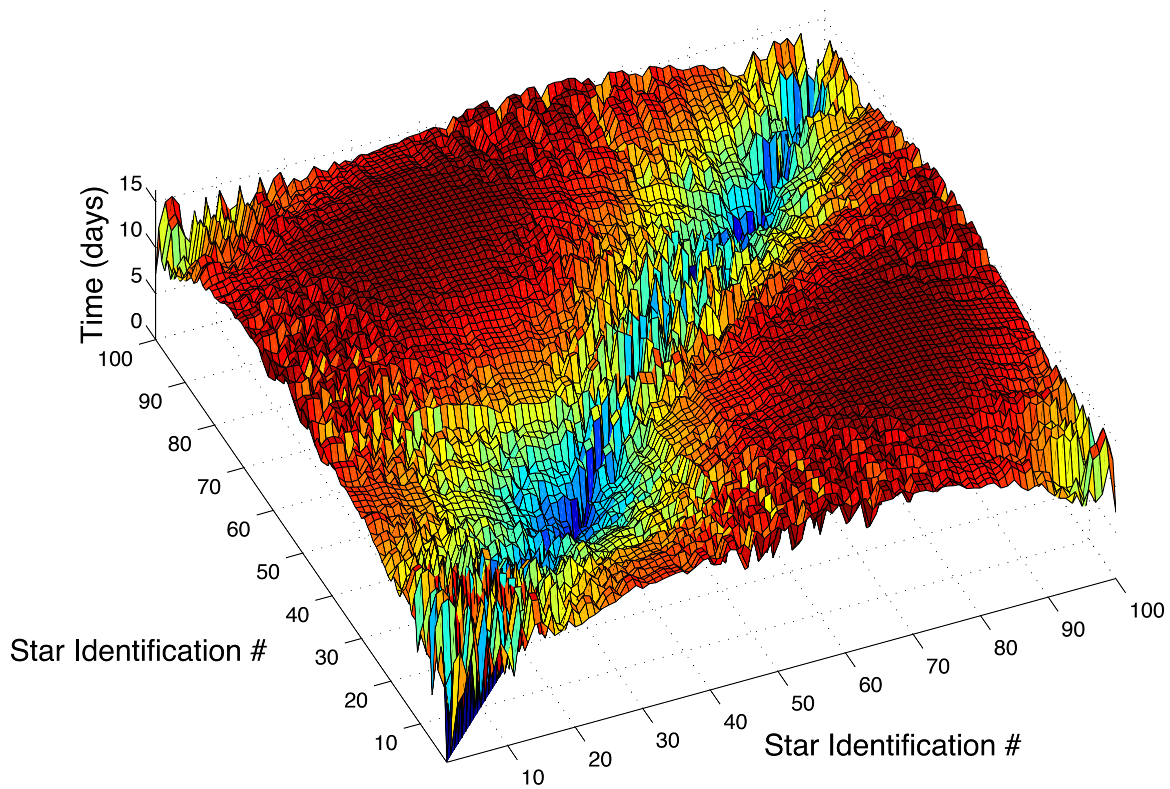
60 m occulter
14 m petals
100 mas IWA (62,000 km)
2 mm gaps and tips
Upgraded NIRCam & NIRSpec filters

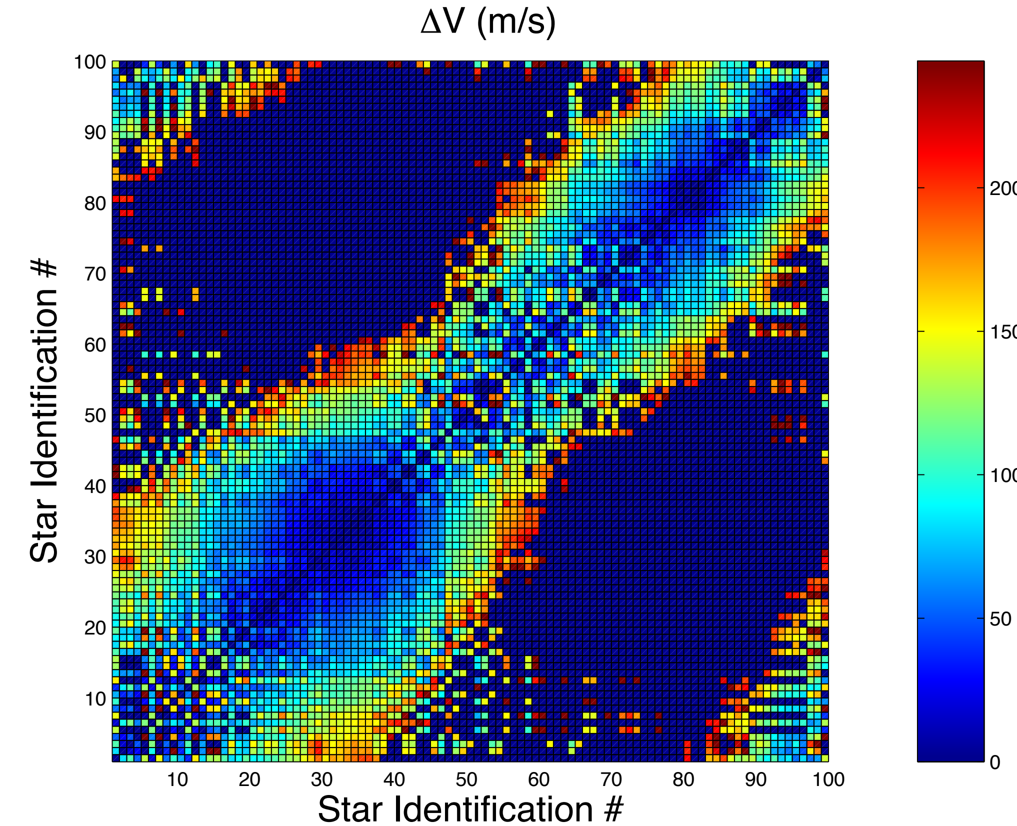
Both occulters tilted 15 degrees for 20 deg field-of-regard

# Science Performance

# Occulter Mission Feasibility

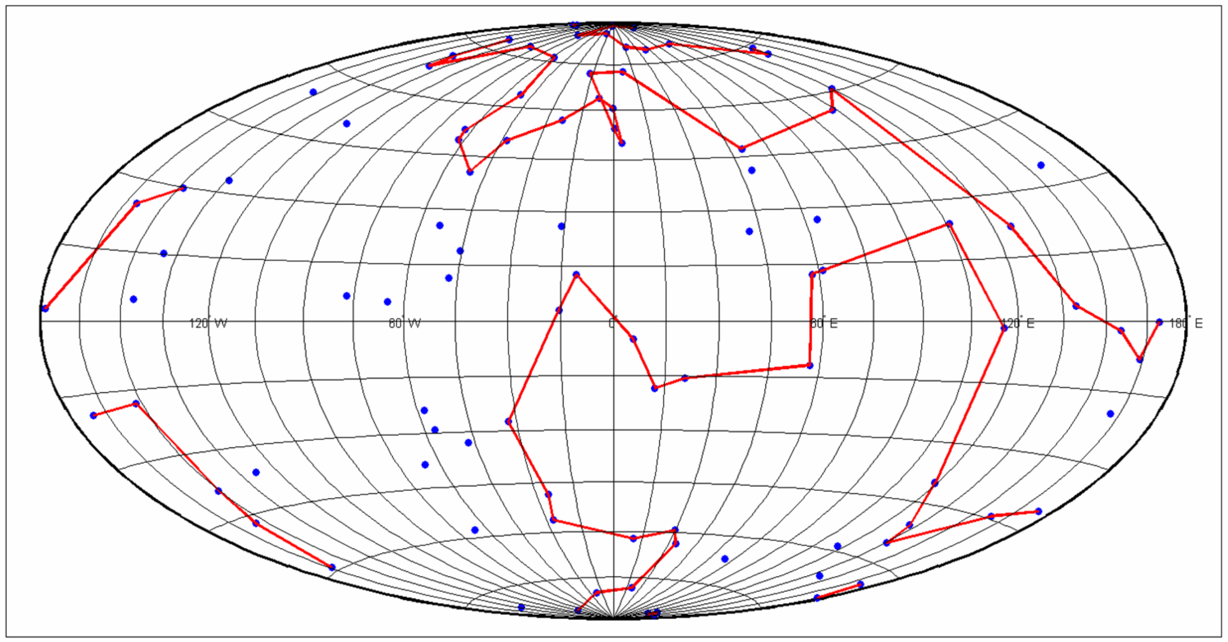
Kolemen et al. (2011)




Minimum time-to-realign between top 100 targets with SMART-1 capabilities (R=50,000 km).

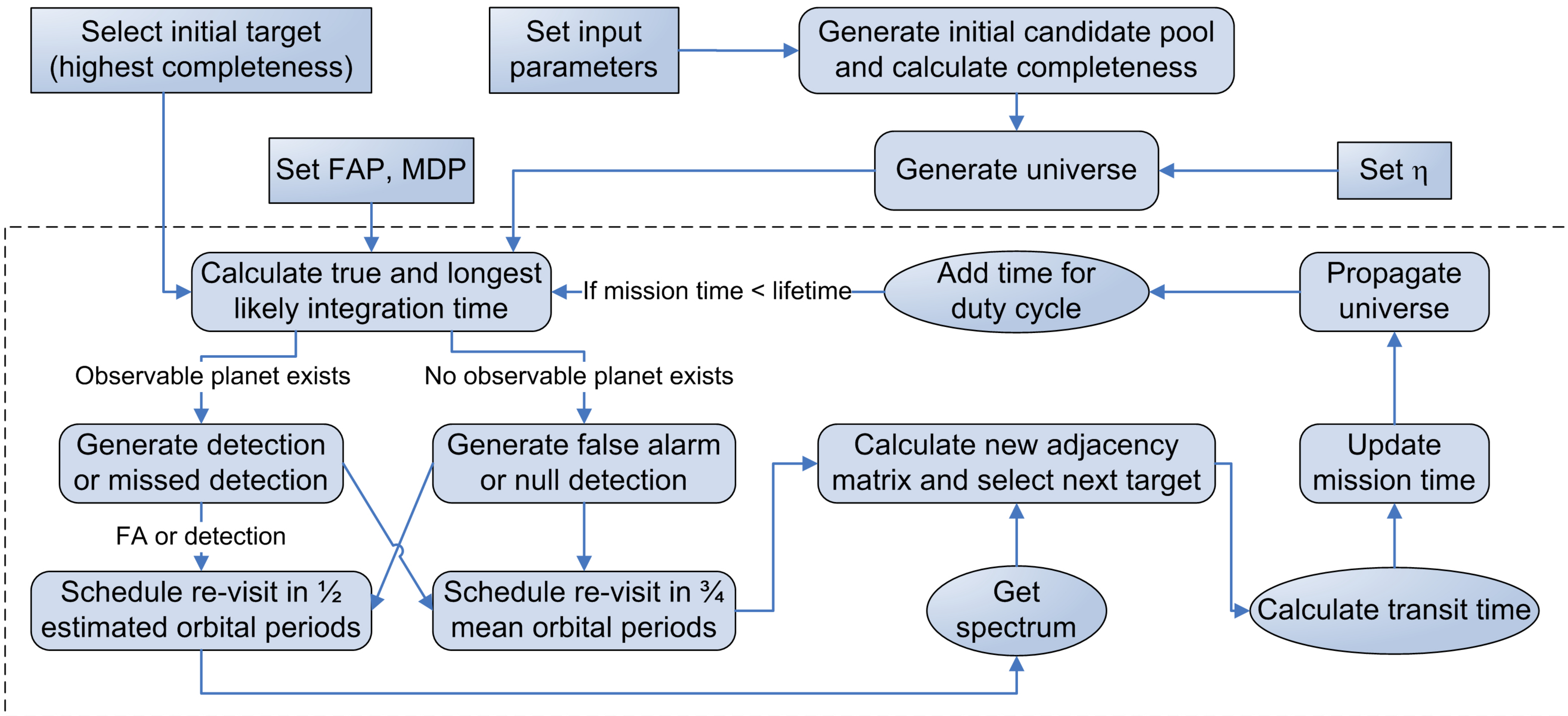
Delta-V to realign between top 100 targets with SMART-1 capabilities (R=50,000 km and Delta-t=2 weeks)



The global optimal solution with 75 imaging sessions of the Top 100 stars, 2 week flight time between targets and no revisits. Found through a Time-Dependent, Dynamic Traveling Salesmen Problem.

# Monte-Carlo Performance Comparisons

Savransky et al. 2009




Automated Monte Carlo Mission Generation

**How many planets can a mission detect and characterize?**

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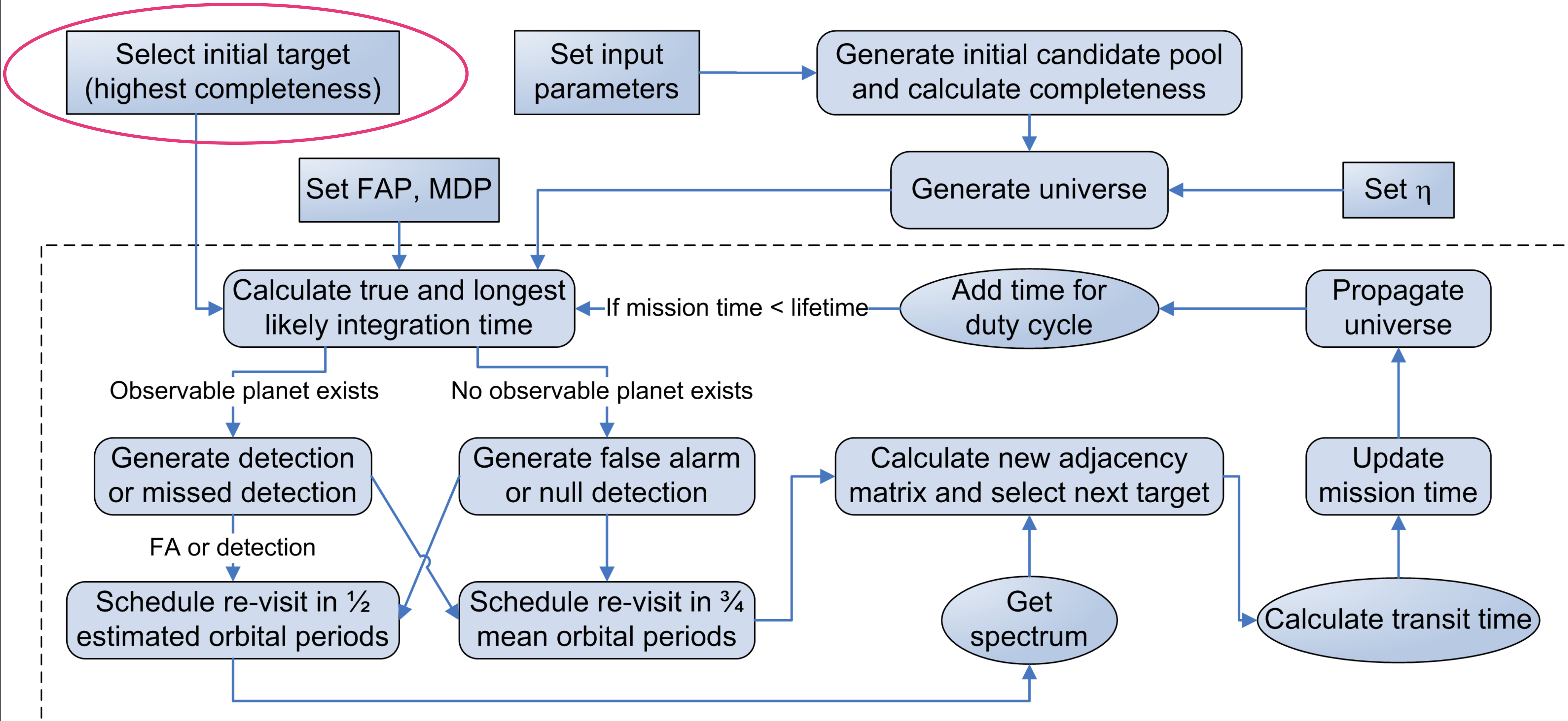


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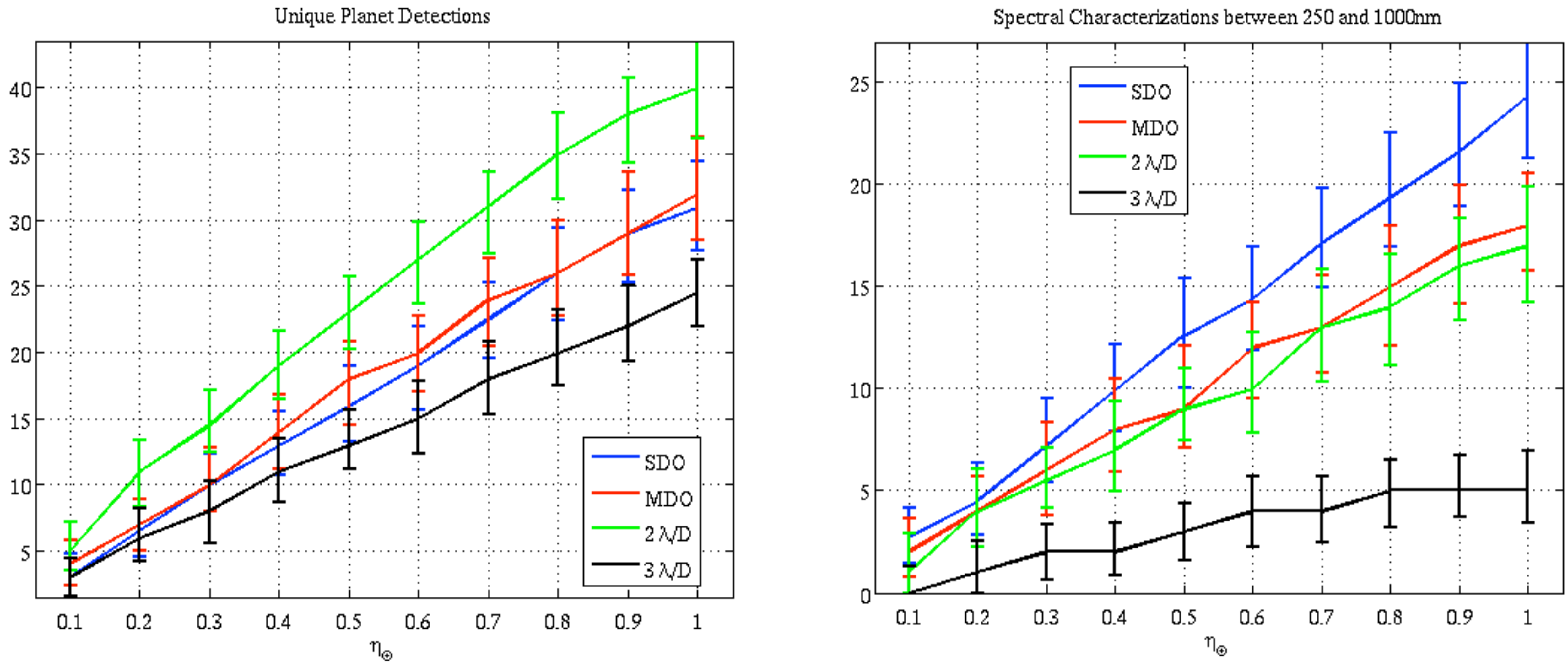
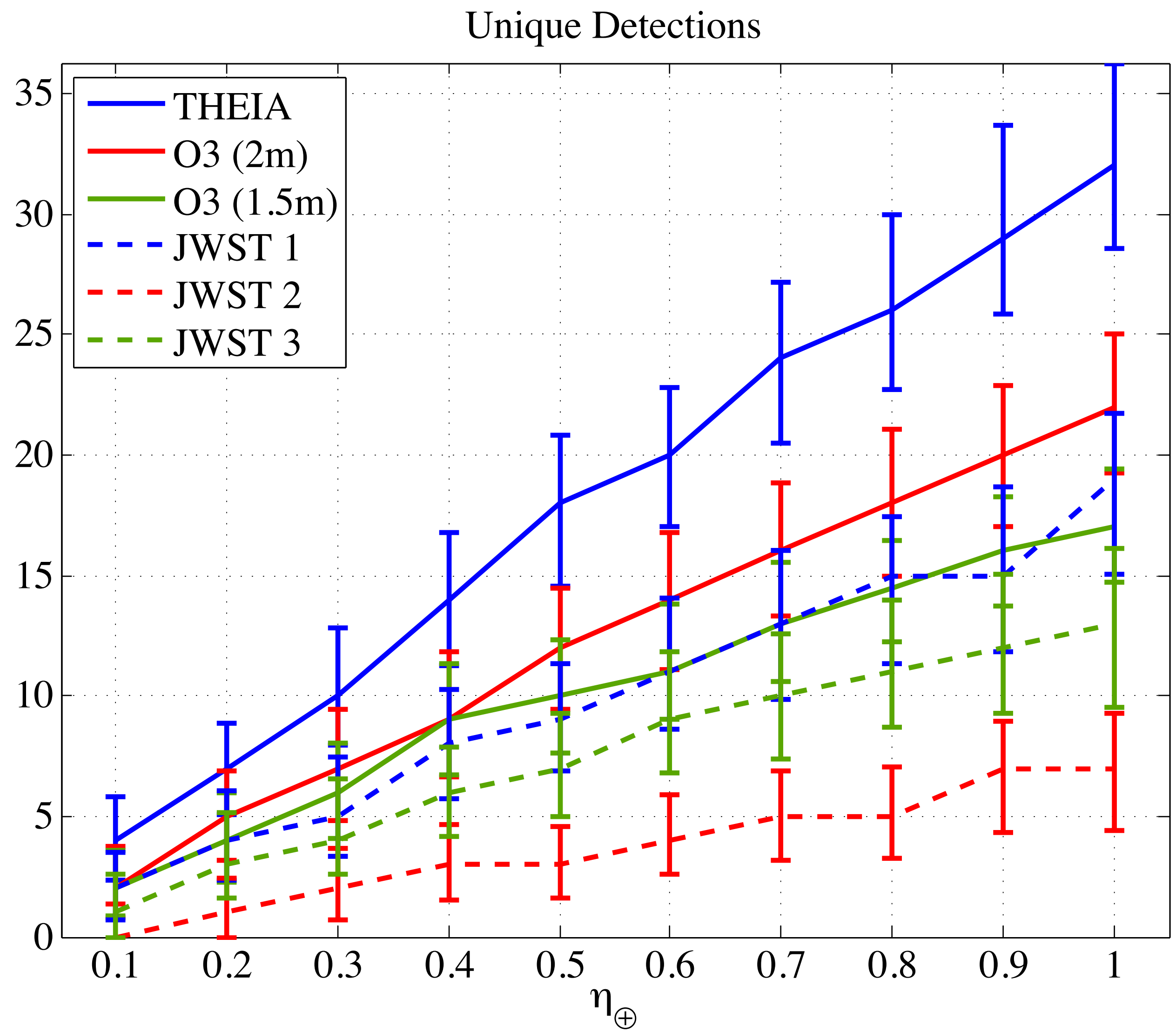
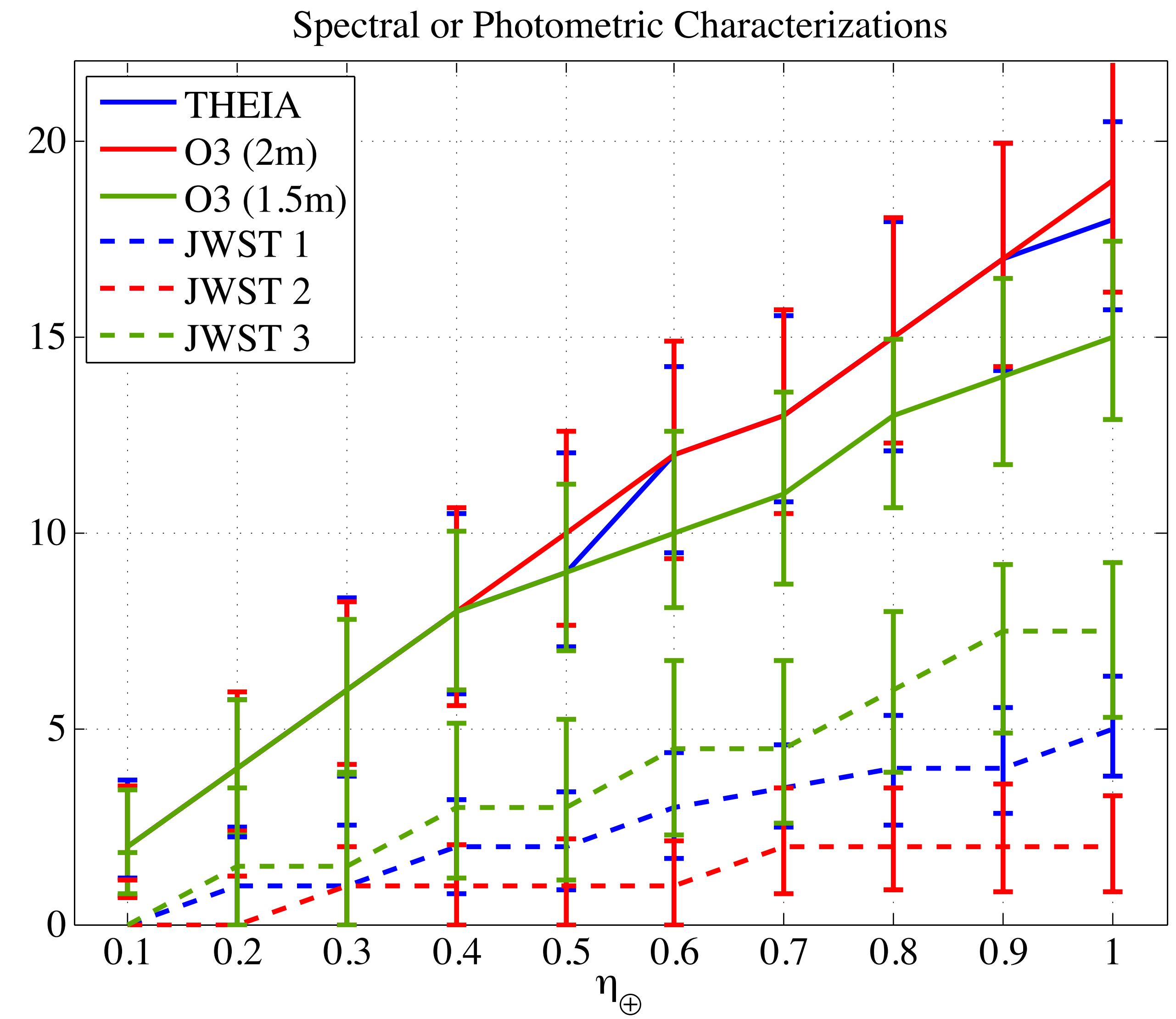
# 4m Telescope




- Almost 40 Earthlike planets detected at eta = 1
- Small variations among approaches (except 3 l/D coronagraph)
- 2 lambda/D coronagraph gets more unique planets and about same number of spectra as MDO
- 3 lambda/D coronagraph gets very few full spectra

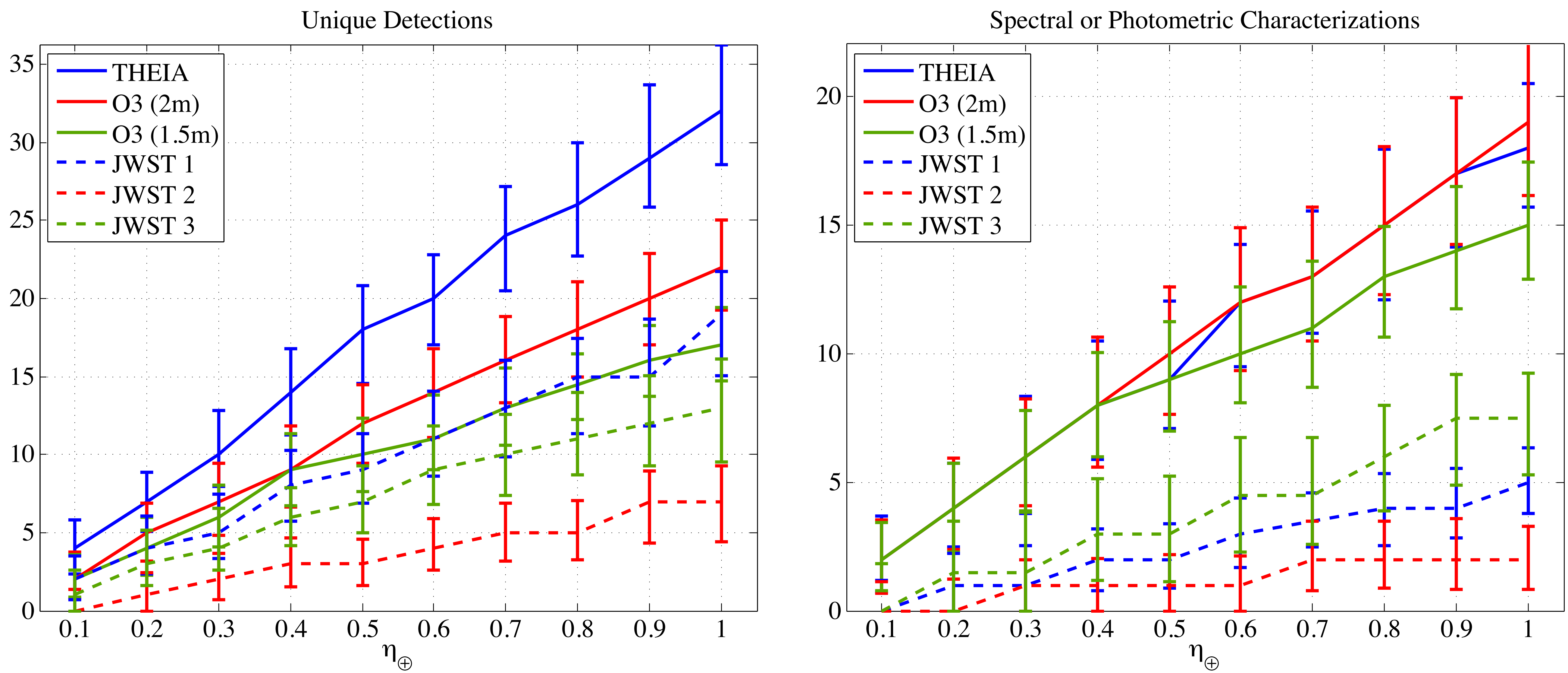
# Occulter Comparison




- THEIA - Spectral characterization from 250 to 1000nm. $O_2$ feature at 760nm to S/N of 11 (Kasdin et al., 2009)
- $O_3$ - Band photometry in blue and red to S/N of 3 (Savransky et al., 2010)
- JWST 1 - Spectral characterization between 950 to 1300 nm. $O_2$ feature at 1260nm.
- JWST 2 - Spectral characterization between 700 and 1700 nm (see Soummer et al., 2010). Same propulsion as THEIA.
- JWST 3 - Same as JWST 2, but with thrust increased to allow average of 70 observations as in Brown and Soummer, 2010

# Occulter Comparison




- THEIA - Spectral characterization from 250 to 1000nm. $O_2$ feature at 760nm to S/N of 11 (Kasdin et al., 2009)

- Note: Other DRMs for JWST with the larger occulter get
- somewhat more planets under slightly simplified assumptions.
- 

2( An optimization would probably fall somewhere in between (2-6

- spectra at eta=0.3).

observations as in Brown and Soummer, 2010


Technology Development

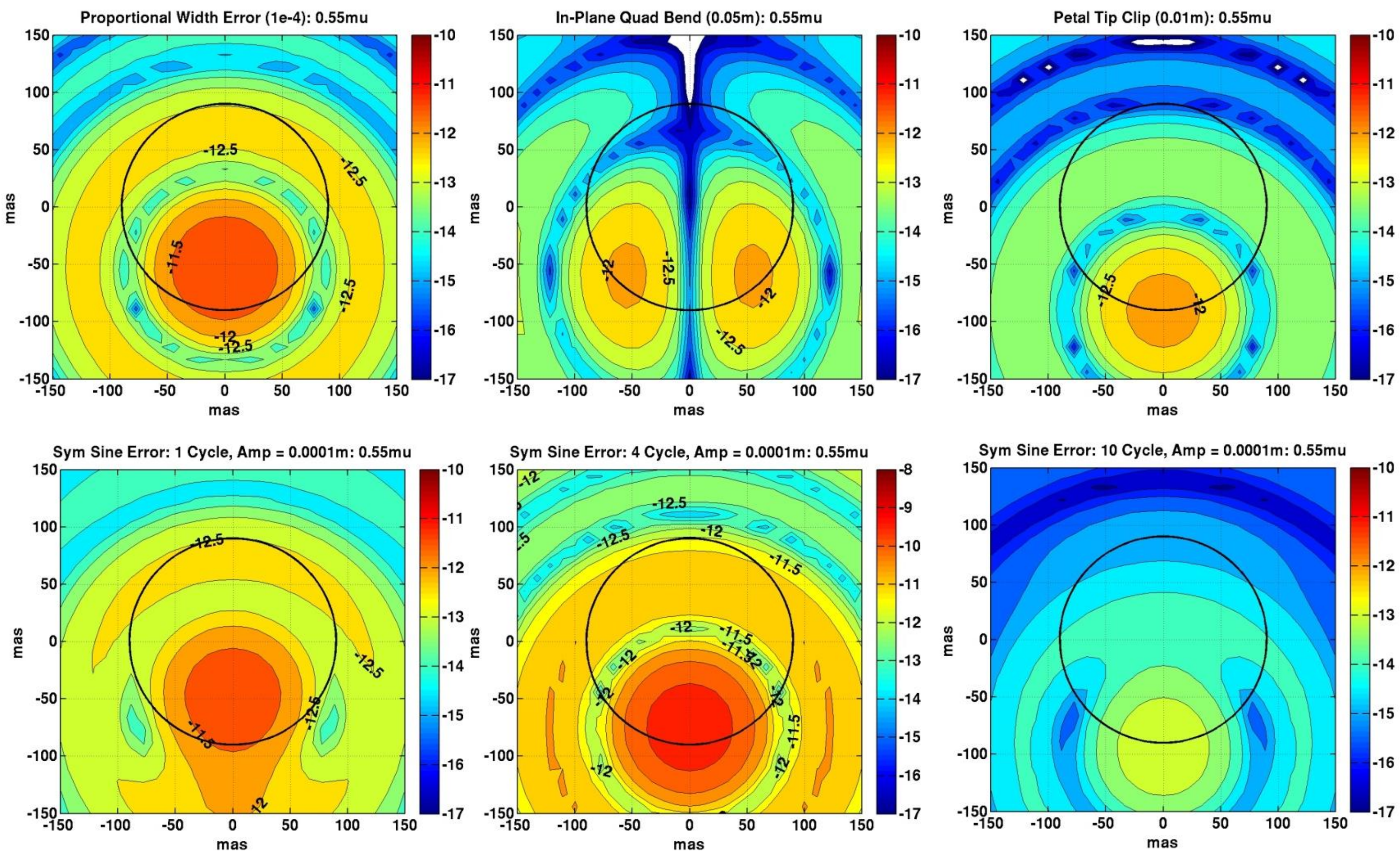
# Technology Challenges

To design and build an occulter that satisfies the requirements and constraints:

- Precision edge shape
- Deployment accuracy
- Validated optical models (software and lab)
- Sensing and Formation control
- Thermal variations
- Dynamic stability
- Solar Glint

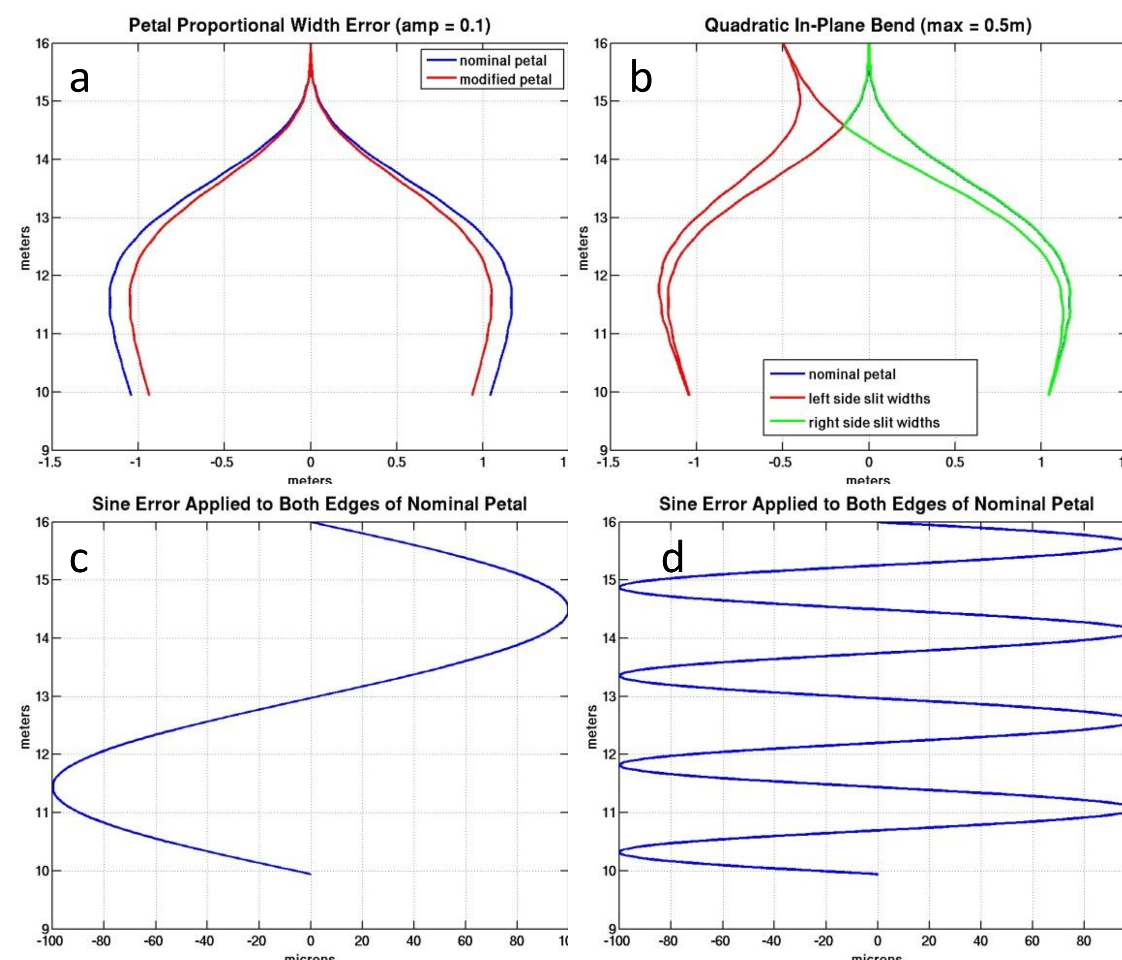
. . . and develop verification and validation aproaches.

# Occulter Shape Error Analysis




Dumont et al. 2010, Shaklan et al. 2010

Contours of image plane contrast for six shape errors. The black circle indicates the angular geometric extent of the petals (90 mas for DI22) as seen by the telescope.




Example petal deformations (highly exaggerated): (a) Proportional shape error. (b) In-plane quadratic bend. (c) The petal edge is displaced by a 1-cycle per petal sine wave. Both sines and cosines were modeled, symmetric and anti-symmetric about the center of the petal. (d) A 4-cycle per petal sine wave error

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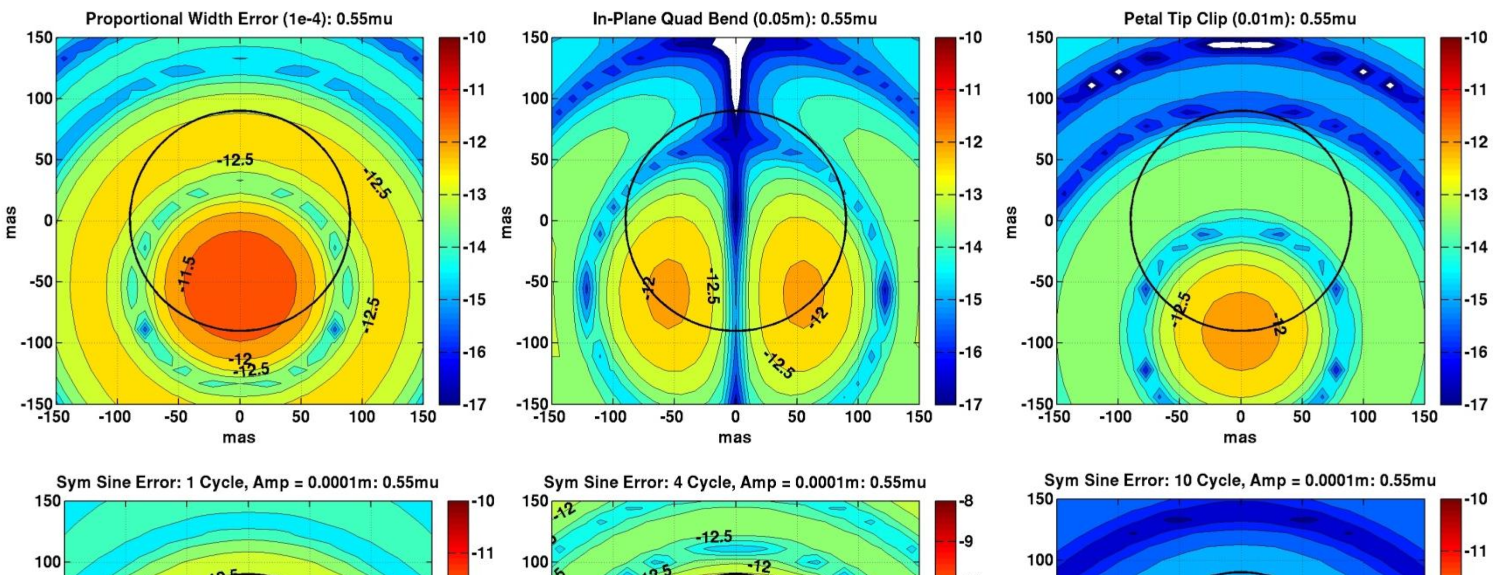


Dumont et al. 2010, Shaklan et al. 2010

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**Independently confirmed via multiple modeling approaches at three different facilities**

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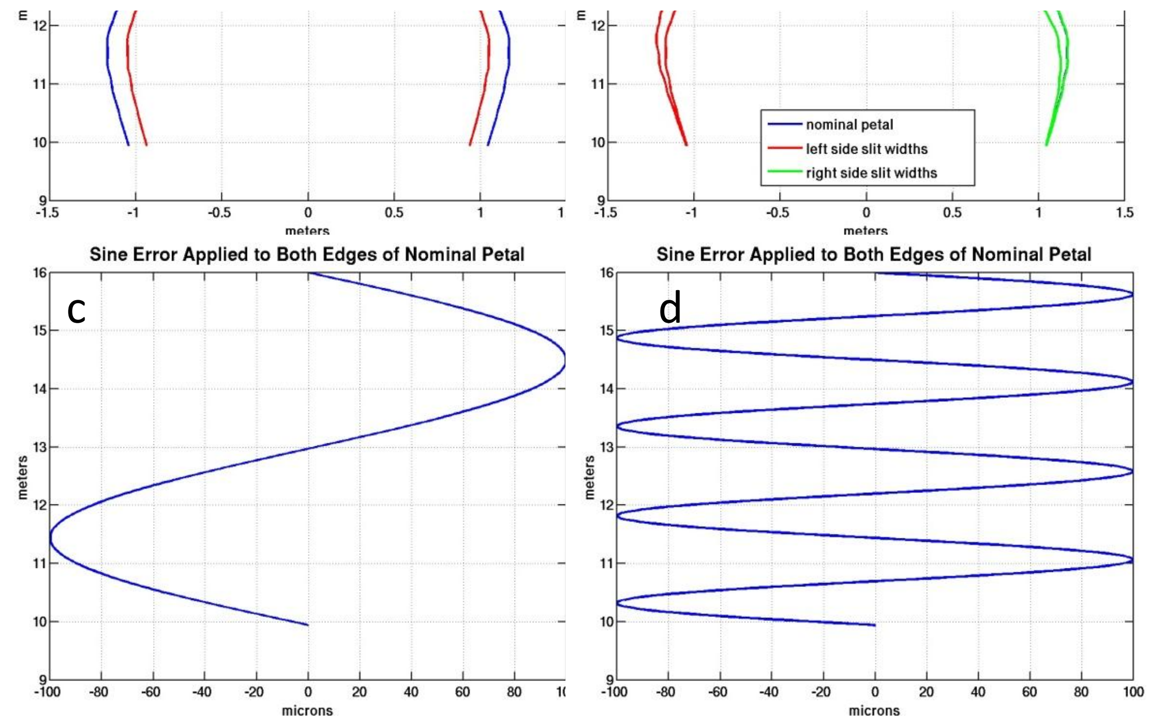


# Occulter Shape Requirements

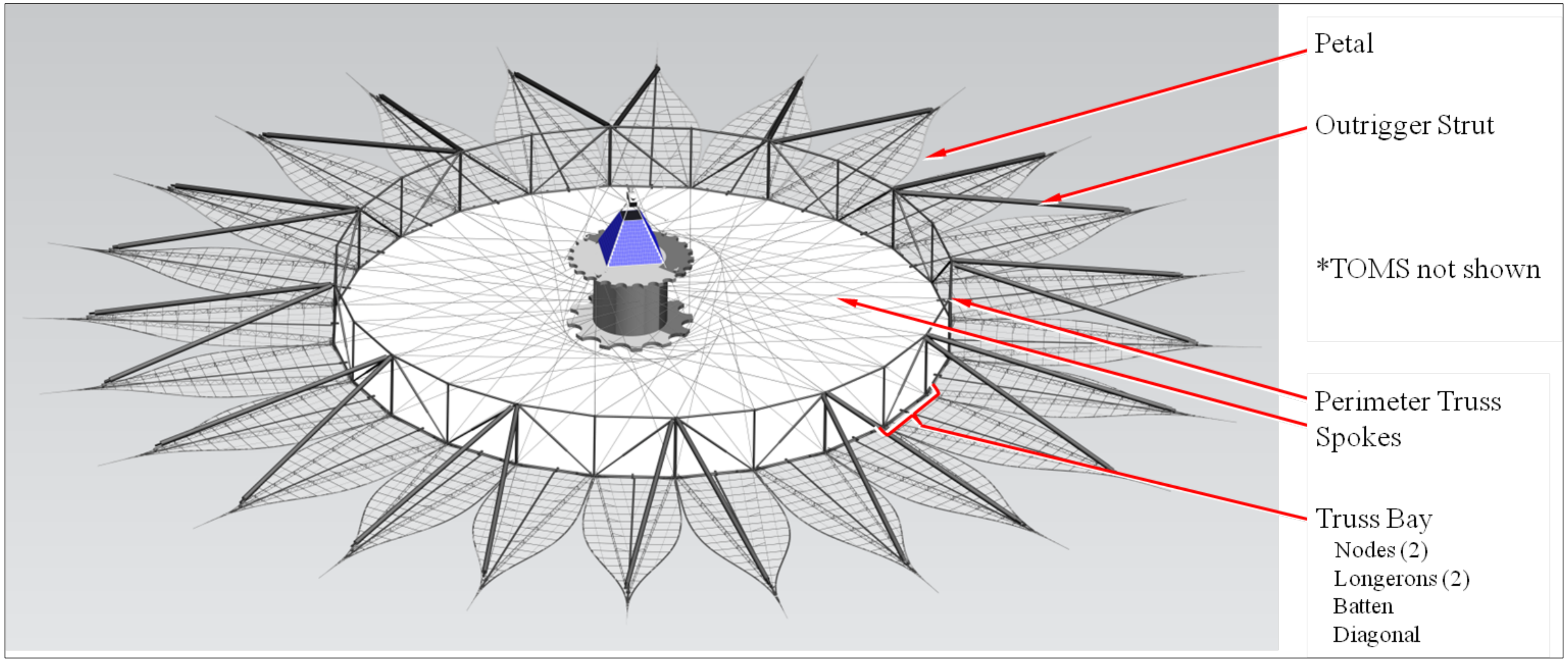
Develop error budget so that sum of intensities (both mean and rms) due to each error maintains suppression at IWA below 3 x $10^{-11}$ (remaining contrast allocated to dynamic and deployment errors).

| Perturbation | Requirement | Units | Mean Contrast |
|---|---|---|---|
| Proportional Width | 7.0E-05 | n/a | 1.5E-11 |
| Tip Clip | 10 | mm | 2.8E-12 |
| In-plane quadratic bend | 20 | mm | 6.5E-13 |
| 1 cycle per petal symmetric | 70.7 | um | 3.5E-12 |
| 2 cycle per petal symmetric | 25.0 | um | 2.7E-12 |
| 3 cycle per petal symmetric | 13.6 | um | 5.9E-12 |
| 4 cycle per petal symmetric | 8.8 | um | 2.1E-11 |
| 5 cycle per petal symmetric | 6.3 | um | 3.8E-12 |
| Symmetric residual > 5 cycles | 12.3 | um | 2.2E-13 |

All are met with a 3-sigma shape error along petal of ~27 microns excluding petal bending and low spatial frequency (1-3 cycles/peta).

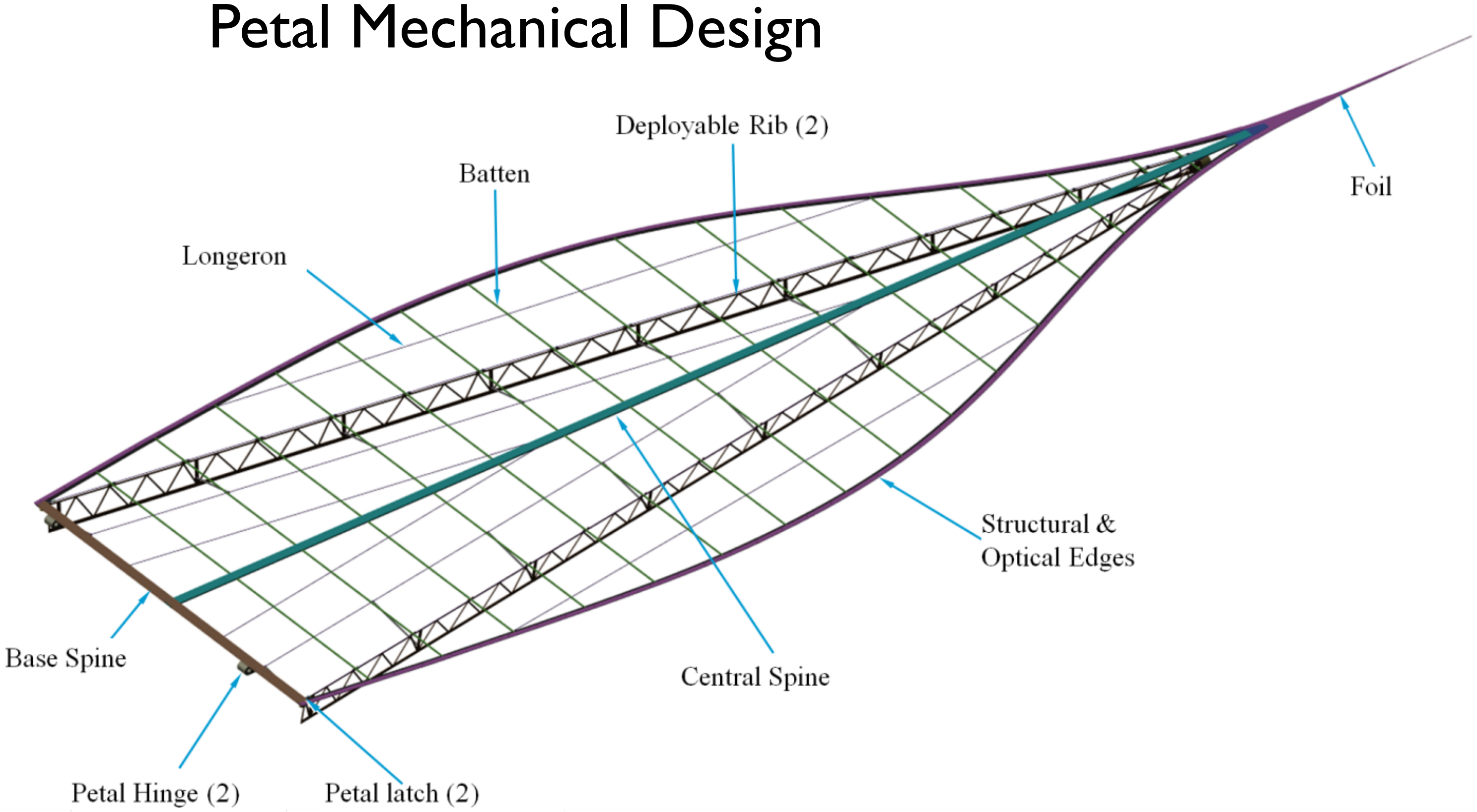
By assuming a spinning occulter, error is dominated by mean rather than rms and is relaxed significantly.

# Mechanical Design – 2010 TDEM



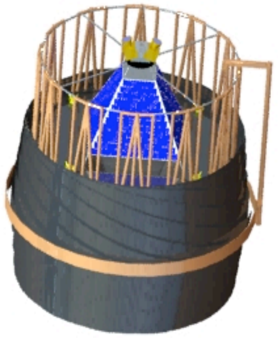

Deployed Starshade, including Petals, Truss, and Spacecraft

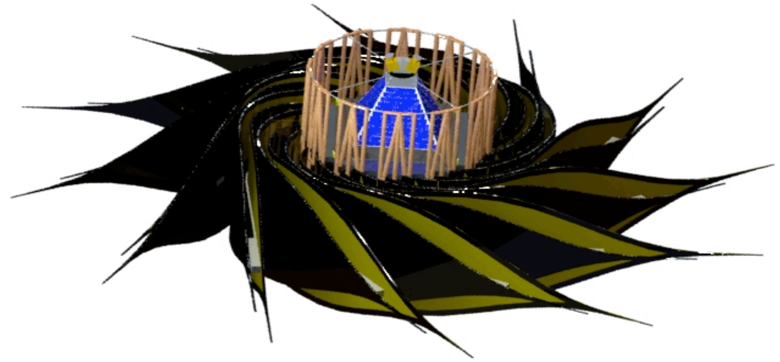
Petal Mechanical Design

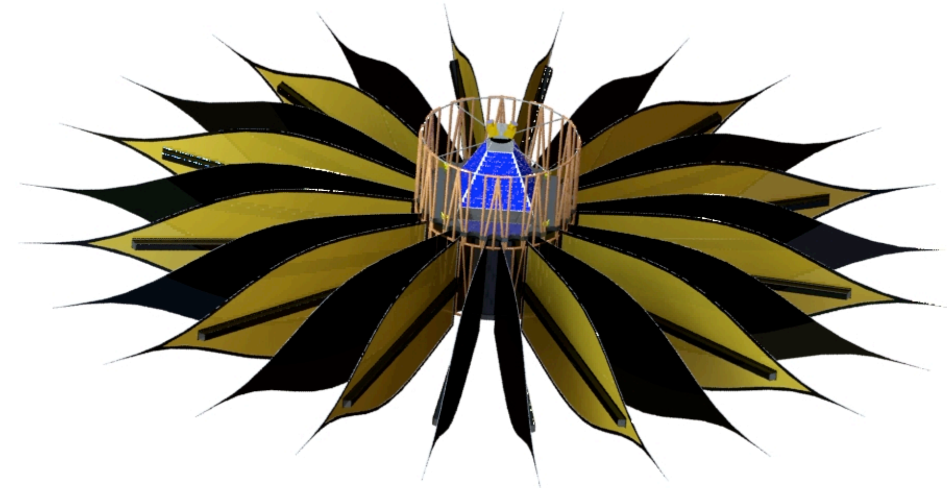



**Objective:**

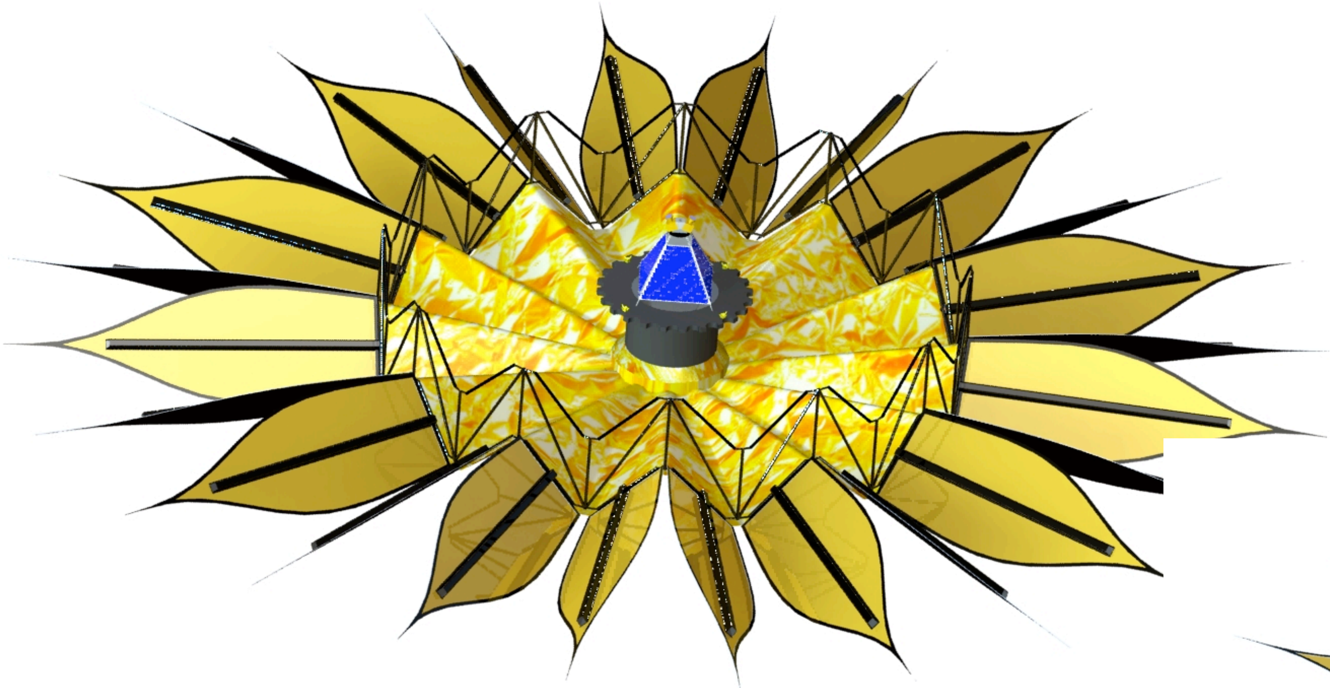
Measure the optical edge position of a full scale petal relative to a fiducial at a sufficient number of locations and with sufficient accuracy to show that, using modeling, a full size occulter with that petal would achieve a contrast of 3 x $10^{-10}$ or better at the IWA with 95% confidence.

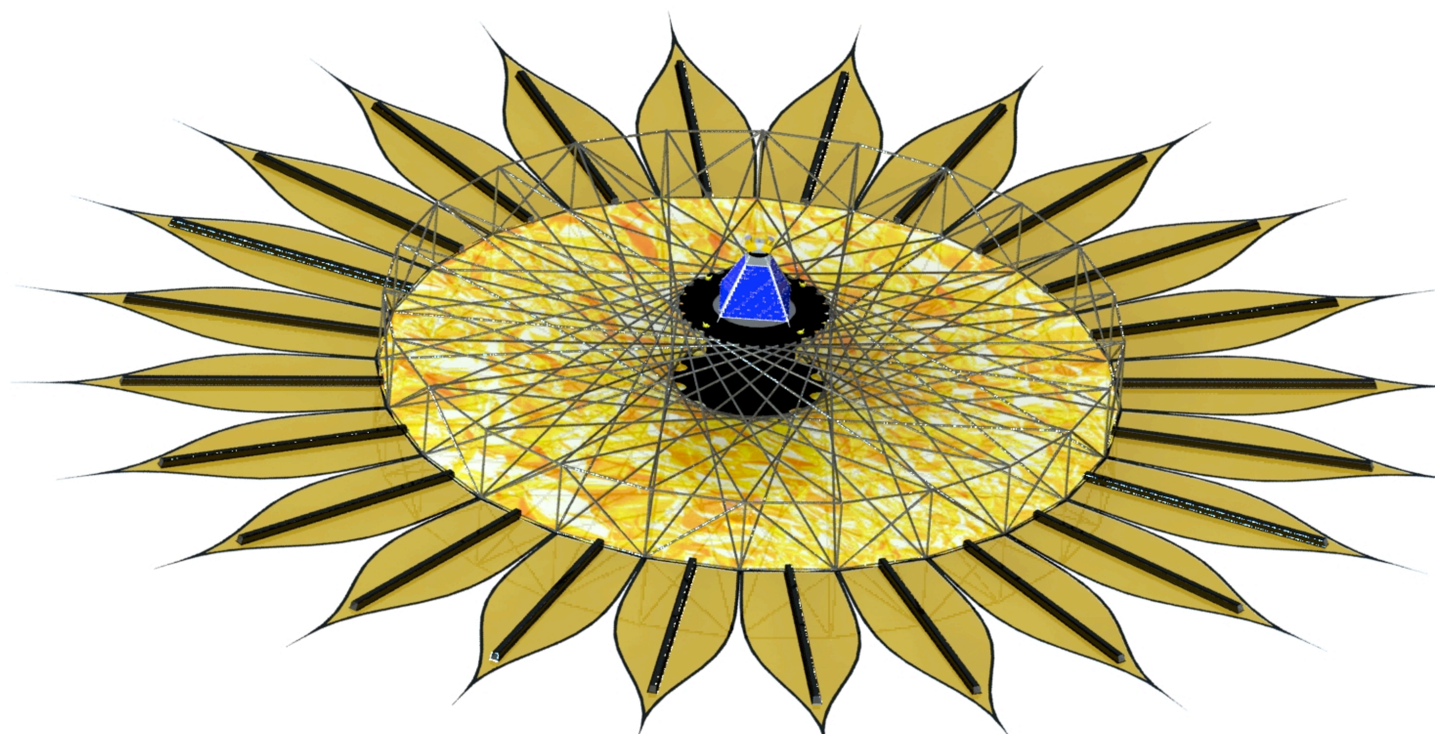




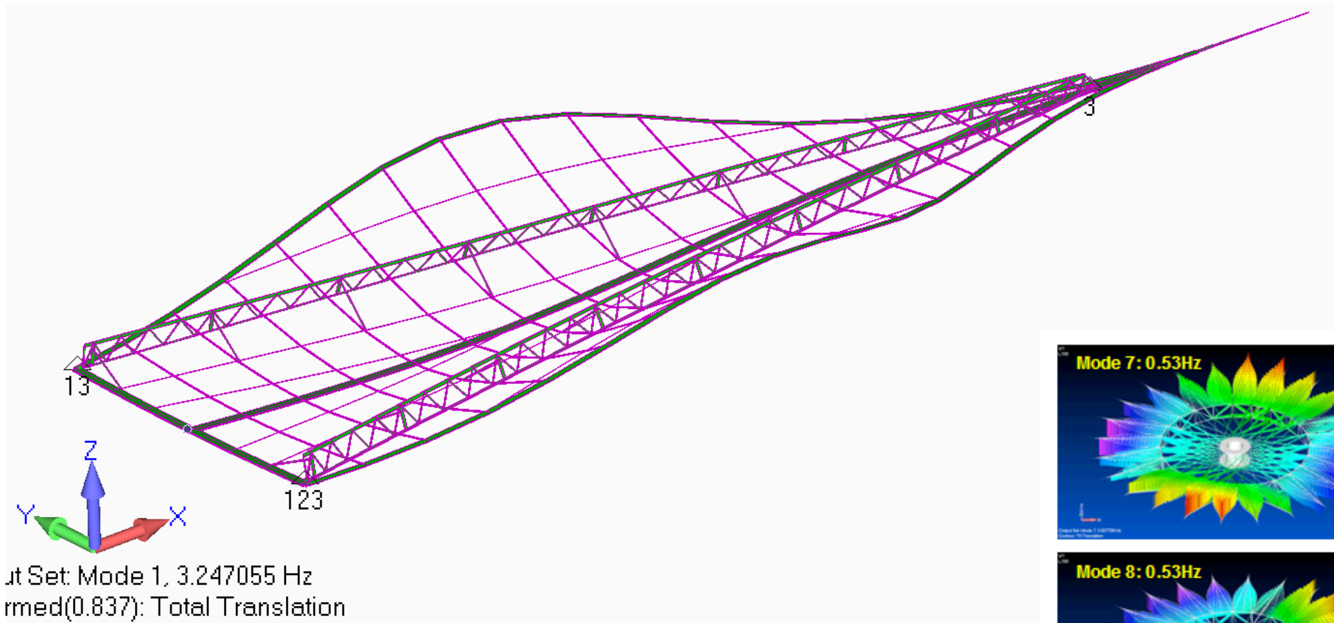


# Starshade Stowage and Deployment

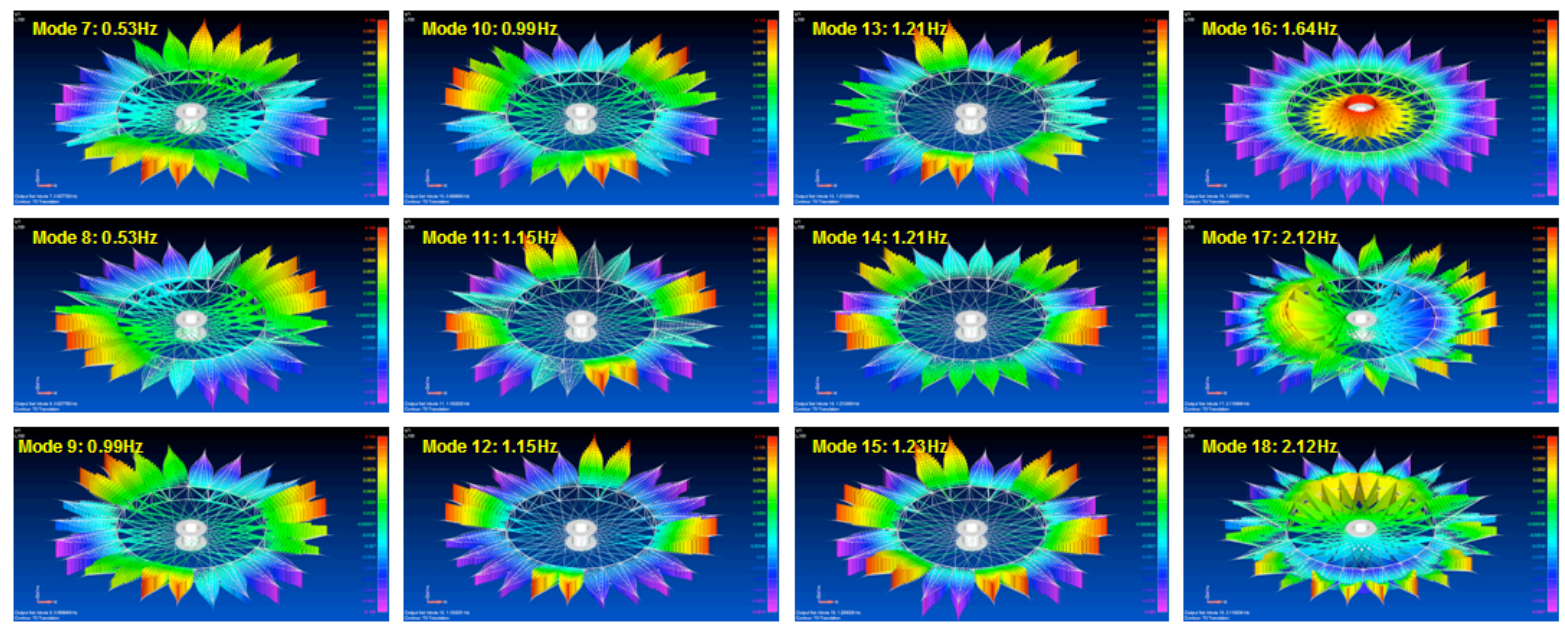




# Preliminary Thermal/Mechanical Model

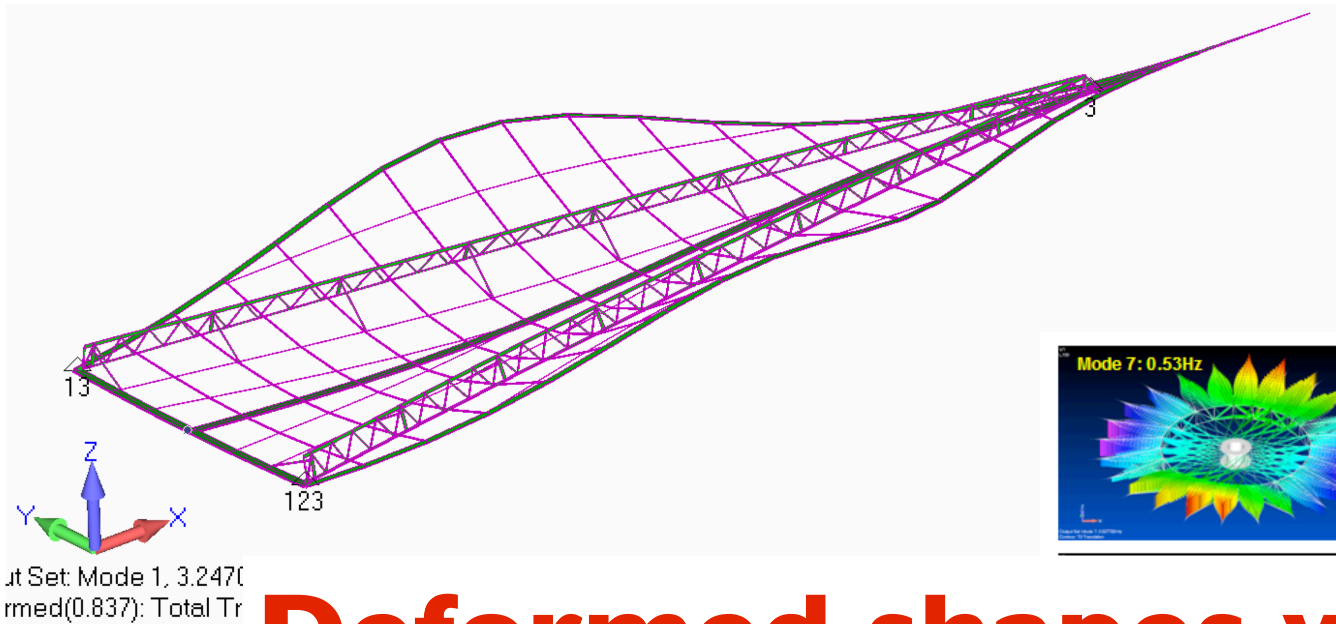



Petal 1st mode (3.2 Hz) mode-shape.



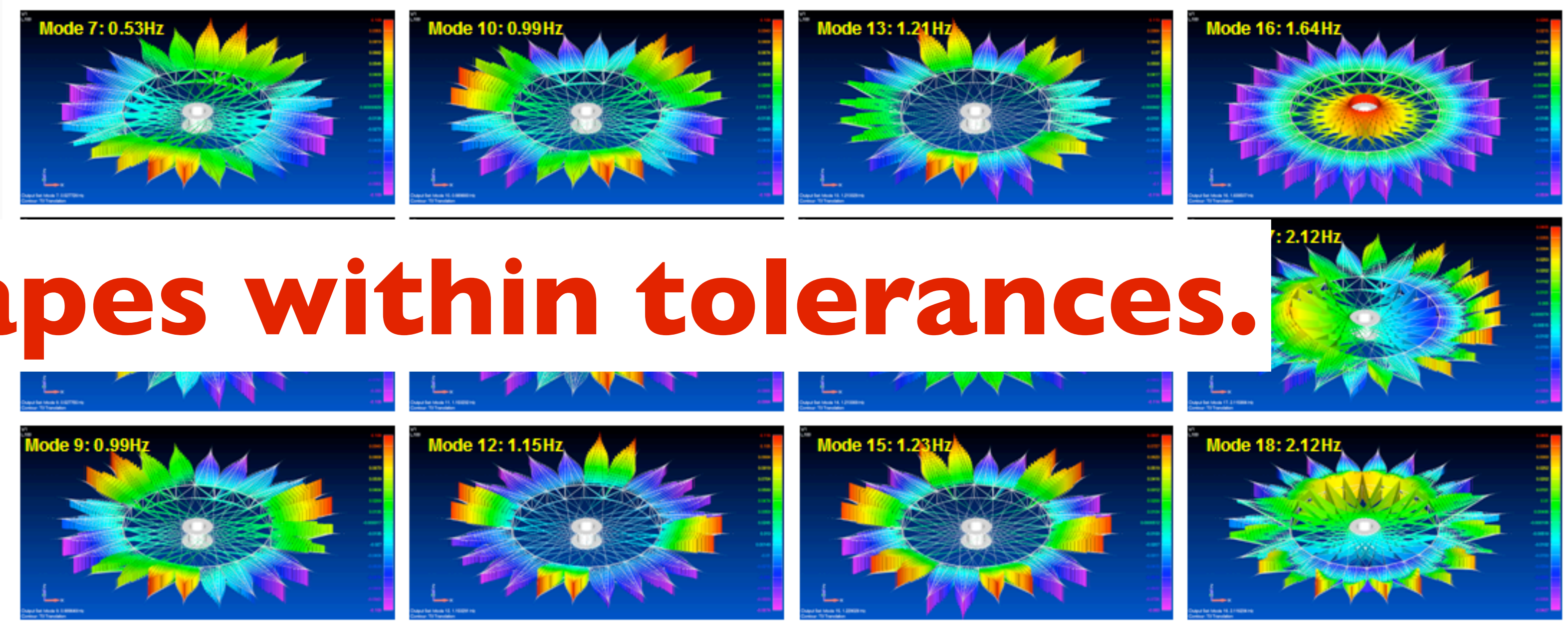

Occulter system normal frequencies and shapes–petals act as rigid bodies.

# Preliminary Thermal/Mechanical Model




Petal 1st mode (3.2 Hz) mode-shape.

**Deformed shapes within tolerances.**




Occulter system normal frequencies and shapes–petals act as rigid bodies.

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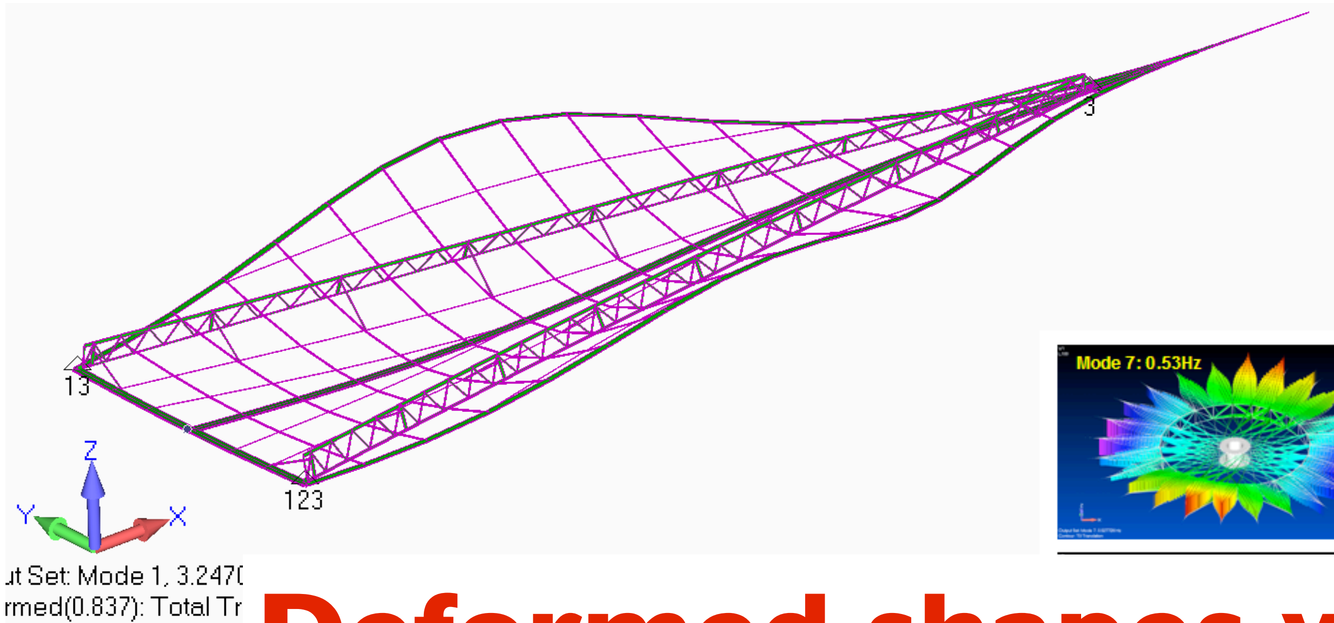


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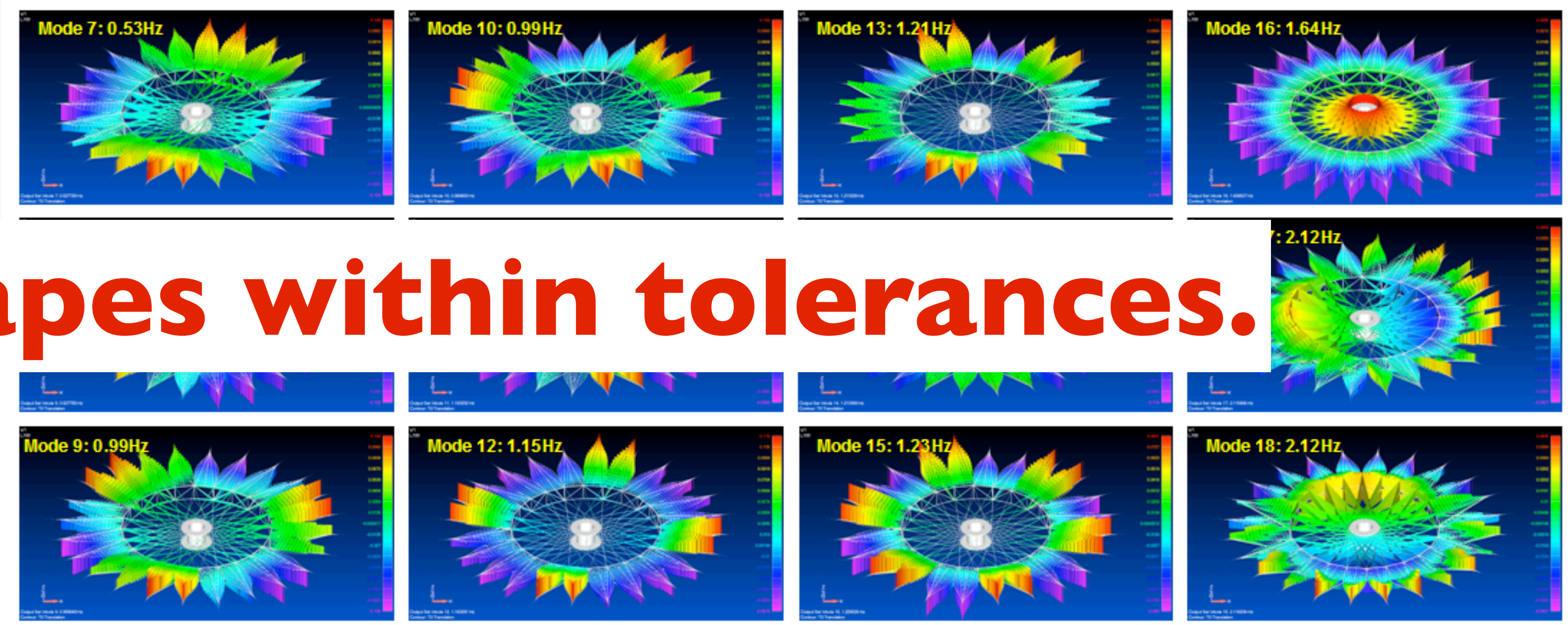
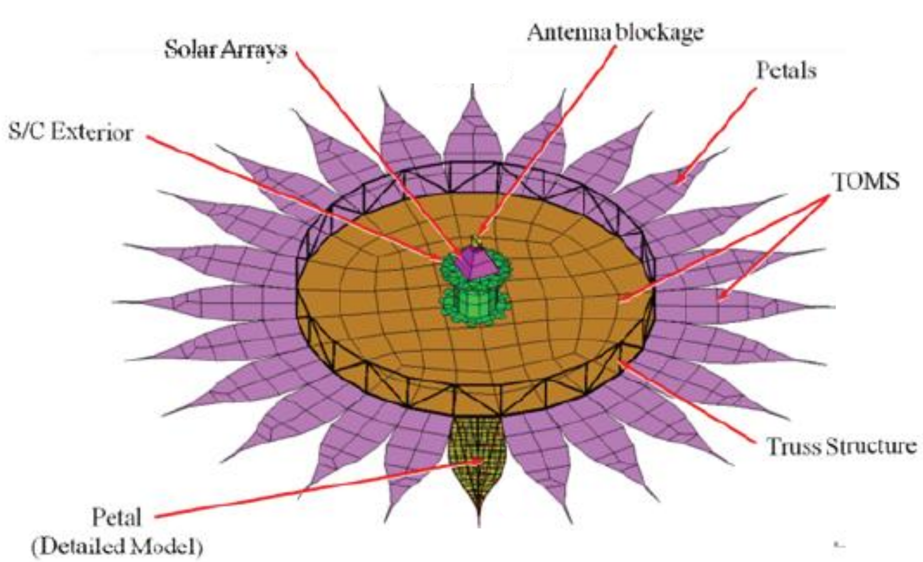
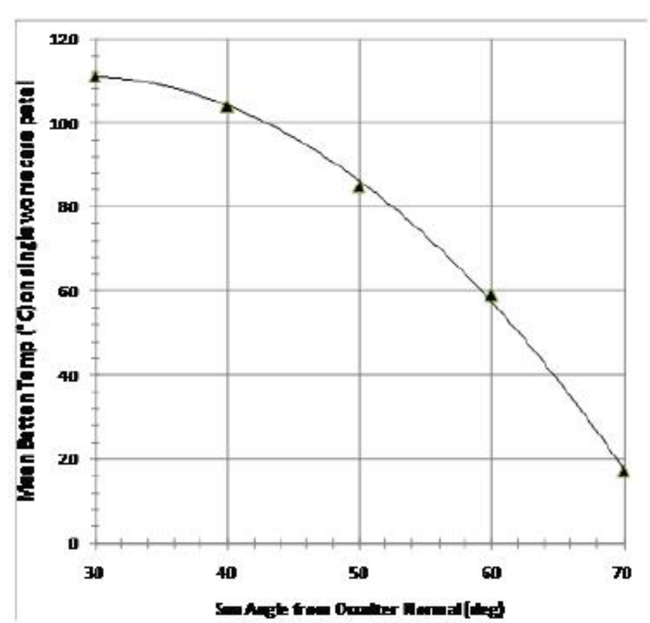



**Deformed shapes within tolerances.**

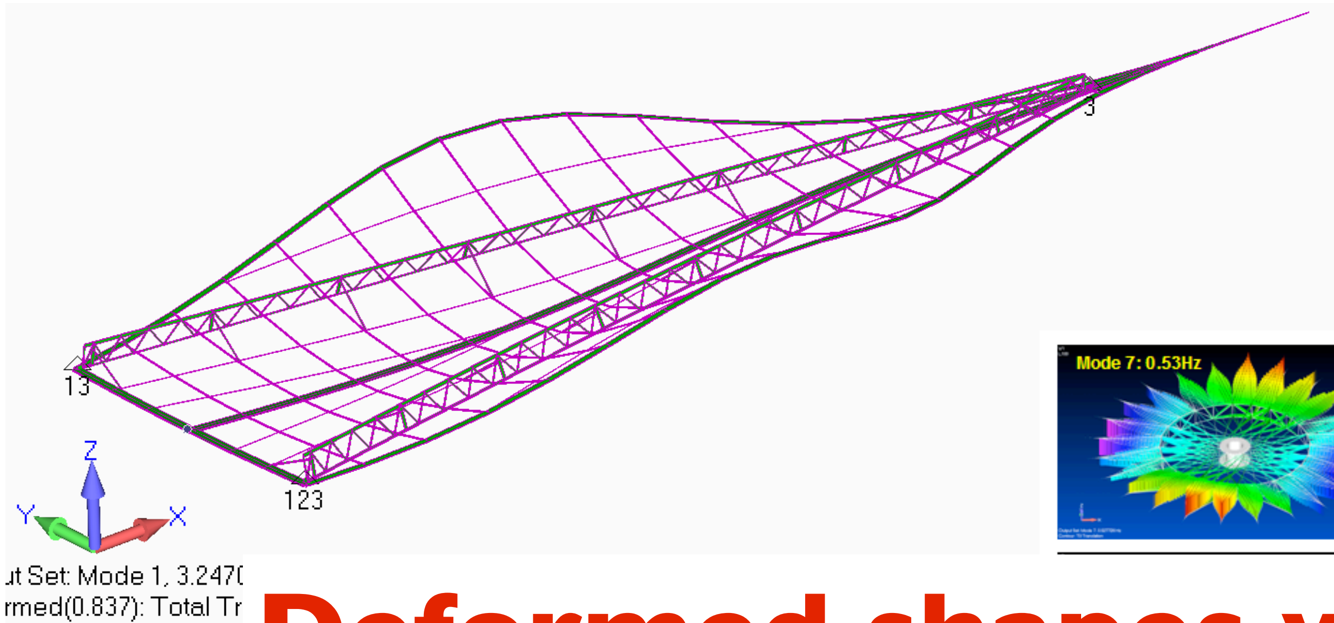
Occulter system normal frequencies and shapes–petals act as rigid bodies.




Occulter thermal model (Left) and Batten temperature vs. sun angle to surface normal (Right).

# Preliminary Thermal/Mechanical Model

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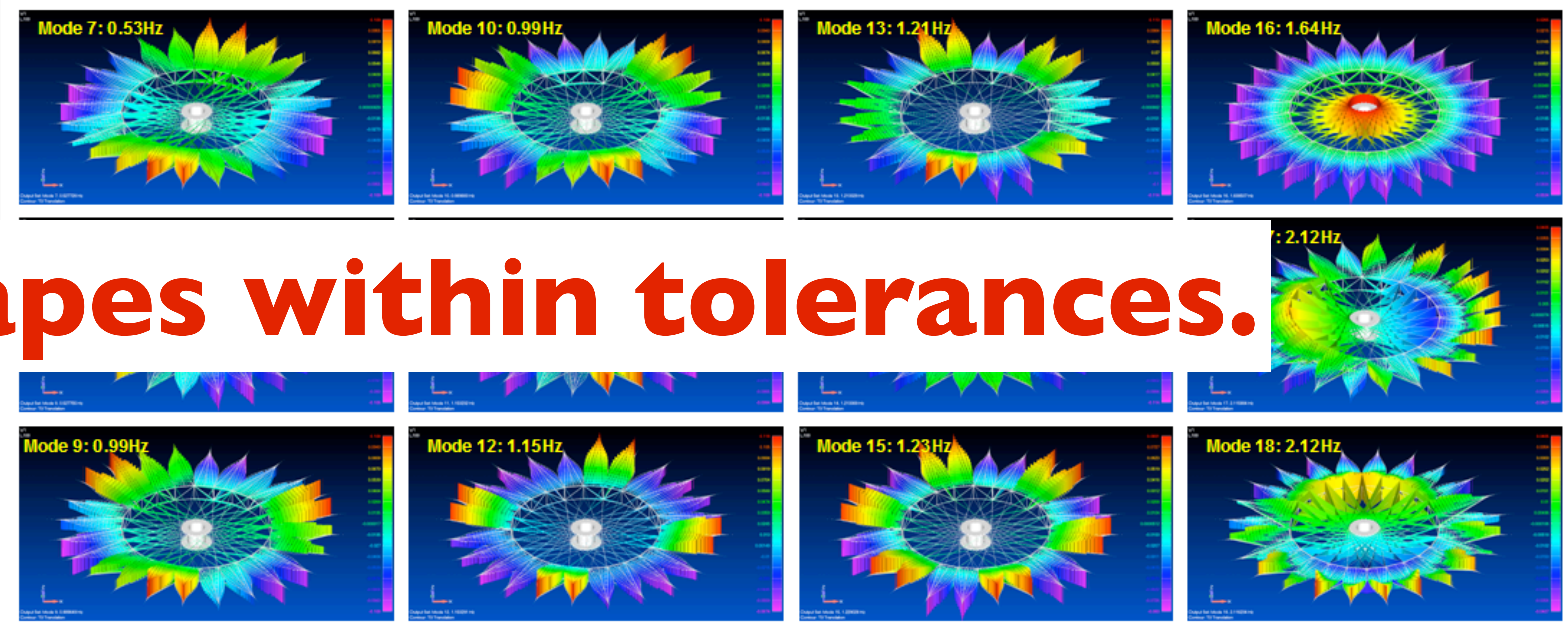
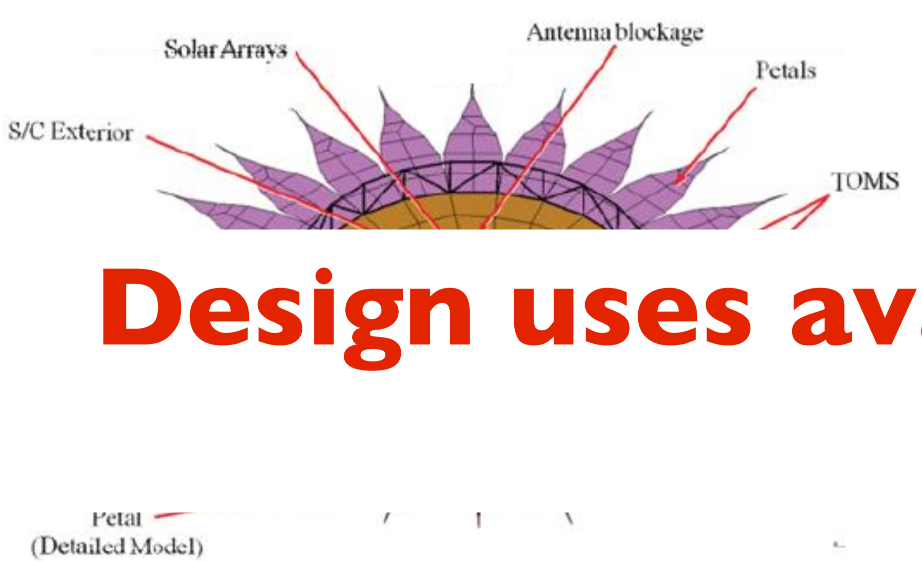
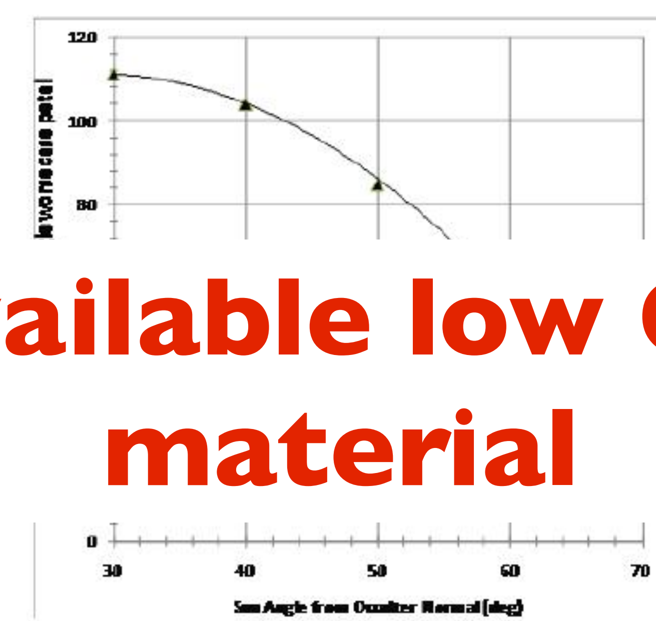



Occulter system normal frequencies and shapes–petals act as rigid bodies.




Occulter thermal model (Left) and

**Design uses available low CTE composite material**


0.14.2010 03:58

# Starshade Petal
# Proof of Concept

# Deployment
# Test

Jet Propulsion Laboratory
California Institute of
Technology



This research was carried out at the Jet Propulsion Laboratory California Institute of Technology under a contract with the National Aeronautics and Space Administration.

# Starshade Technology Tall Poles

## Tallest Poles

- Petal manufacturing tolerance = ± 25 μm in width for max width of 2.5m
- Petal thermal deformation tolerance = ± 25 μm in width for $\Delta$T up to 100 °C
  - Need CTE of ± 0.1 ppm/°C, stock material gives ± 0.16 ppm
- Edge scatter of sunlight ≤ Exo-zodi, expect radius of curvature < 50 μm

## Poles of Lesser Stature

- Petal deployment tolerance = ± 1mm at root and ± 2.5 cm at tip
  - Inner disk truss controls root position & heritage antennas have demonstrated this capability
- Occulter alignment with telescope = ± 1.5 m (excess shadow relative to aperture)
  - Occulter position error is sensed by dedicated channel of exoplanet camera, at long wavelengths, and transmitted to occulter
  - Control loop time is long (typically > 200s) for μg differential gravity between spacecraft
- In-plane dynamic deformations
  - Short transients are OK and truss quickly damps transients from bus (e.g., thruster firings)
  - Petals are stiff relative to truss and do not participate in system modes
- Petal shape stability with stow/deploy cycles
  - Members that control width are not stressed in stowed configuration

# Starshade Technology Roadmap →

## Completed Activities

Develop reference design & analytical models

Build Proof of Concept Petal & demo deploy function

## Current Activities including TDEM 1

Build breadboard petal

Demo manufacturing tolerance

Demo shape stability w/ stow/deploy

Demo edge scatter performance

Characterize CTE at coupon level

## Future Activities at TDEM funding level

Demo thermal deformations

Characterize CTE at assy level

HW in-the-loop Stationkeeping

Precision metrology (if needed)

## Future Activities at >> TDEM funding level (pre-Phase A)

Develop system prototype Including truss

Demo deployment accuracy

Validate structural model

## Why we should worry about "downselecting" too early . . .

Or, what keeps me up at night . . . it is not about losing.

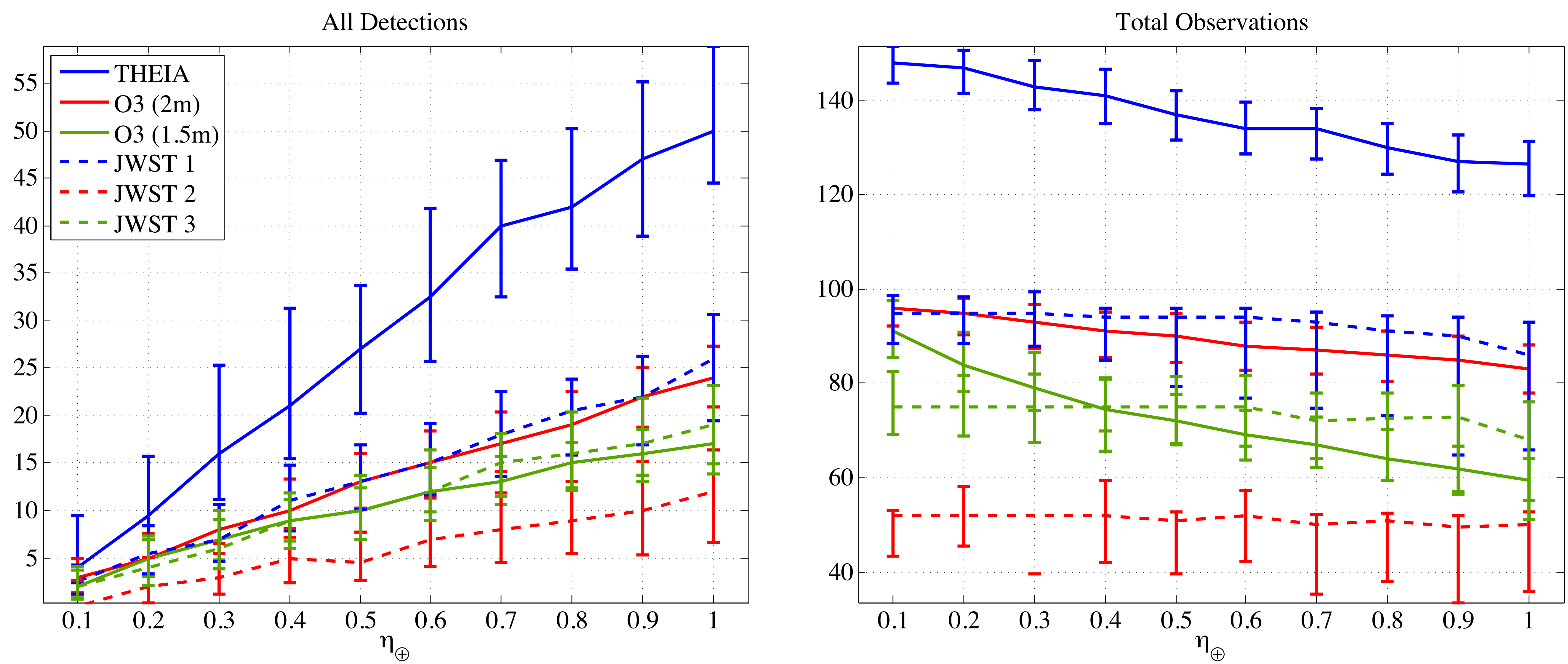
- It may be impossible to find a combination of materials with low enough CTE for an occulter to maintain its shape over wide swings in temperature and thermal gradients.
- It may be impossible to achieve the picometer precision needed on a DM to get ~ $10^{-11}$ contrast (laws of physics might work against us)
- It may be impossible to make a ≥ 4 m telescope stable enough to maintain contrast between corrections

# Thanks

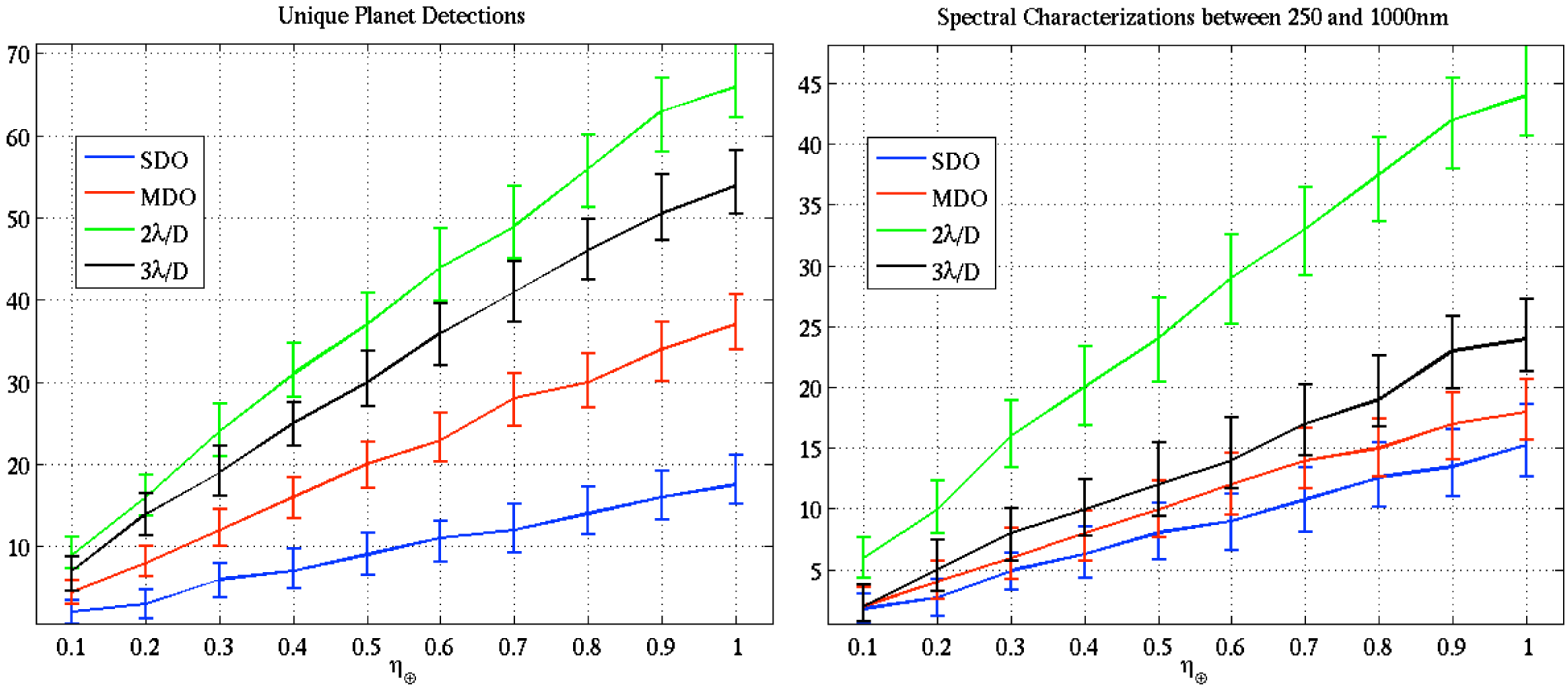
Doug Lisman, Stuart Shaklan, Phil Dumont, Mark Thomson, Eric Cady (JPL), Dmitry Savransky, Dan Sirbu, Bob Vanderbei, David Spergel (Princeton), Dom Tenerelli, Dave Putnam (Lockheed-Martin), Bruce Macintosh, Rob Rudd (Lawrence Livermore), Julie Mikula, Dana Lynch (NASA Ames), Charley Noecker, Roger Linfield (BATC)

# Backup Slides

# Occulter Comparison (backup)

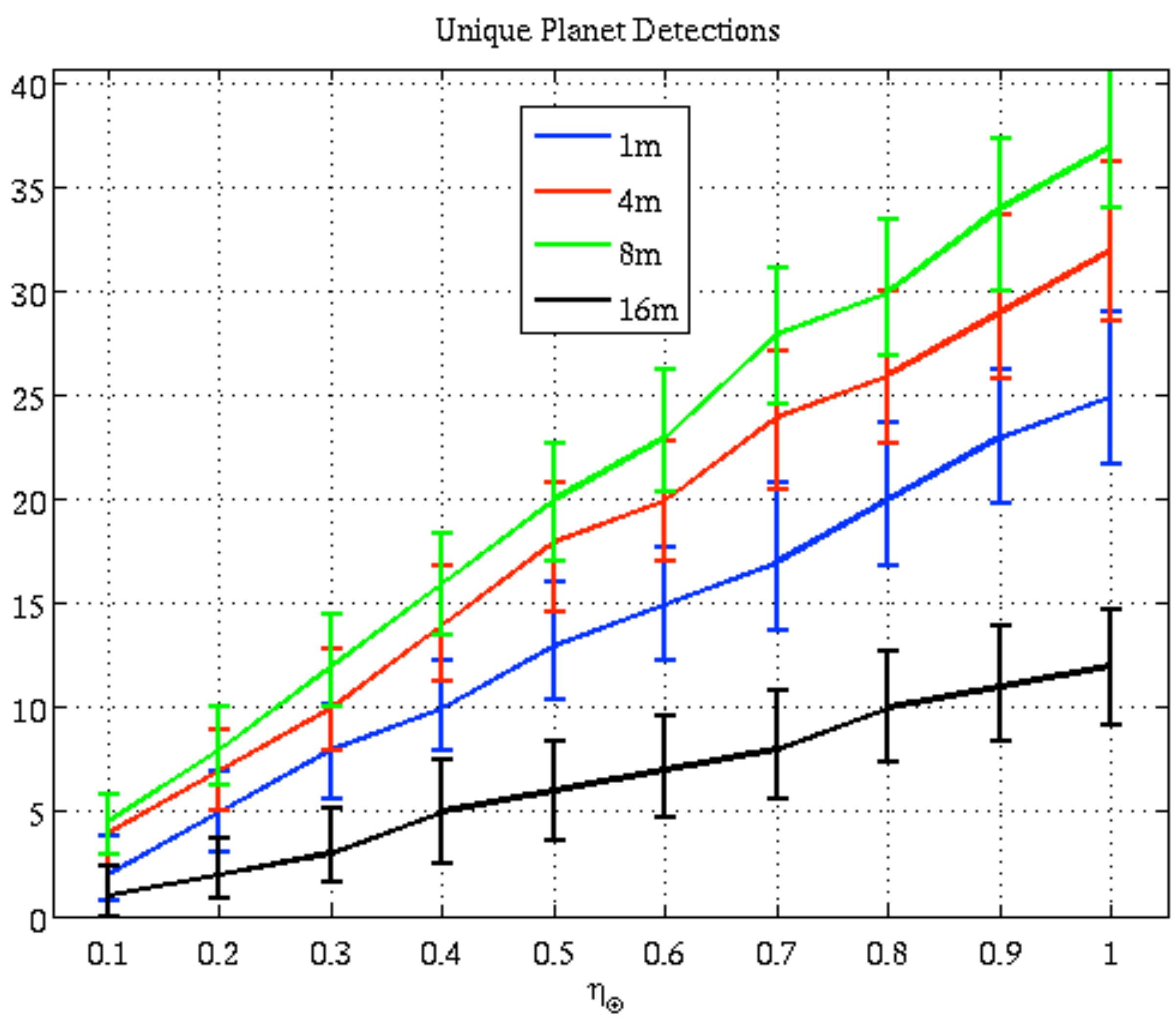


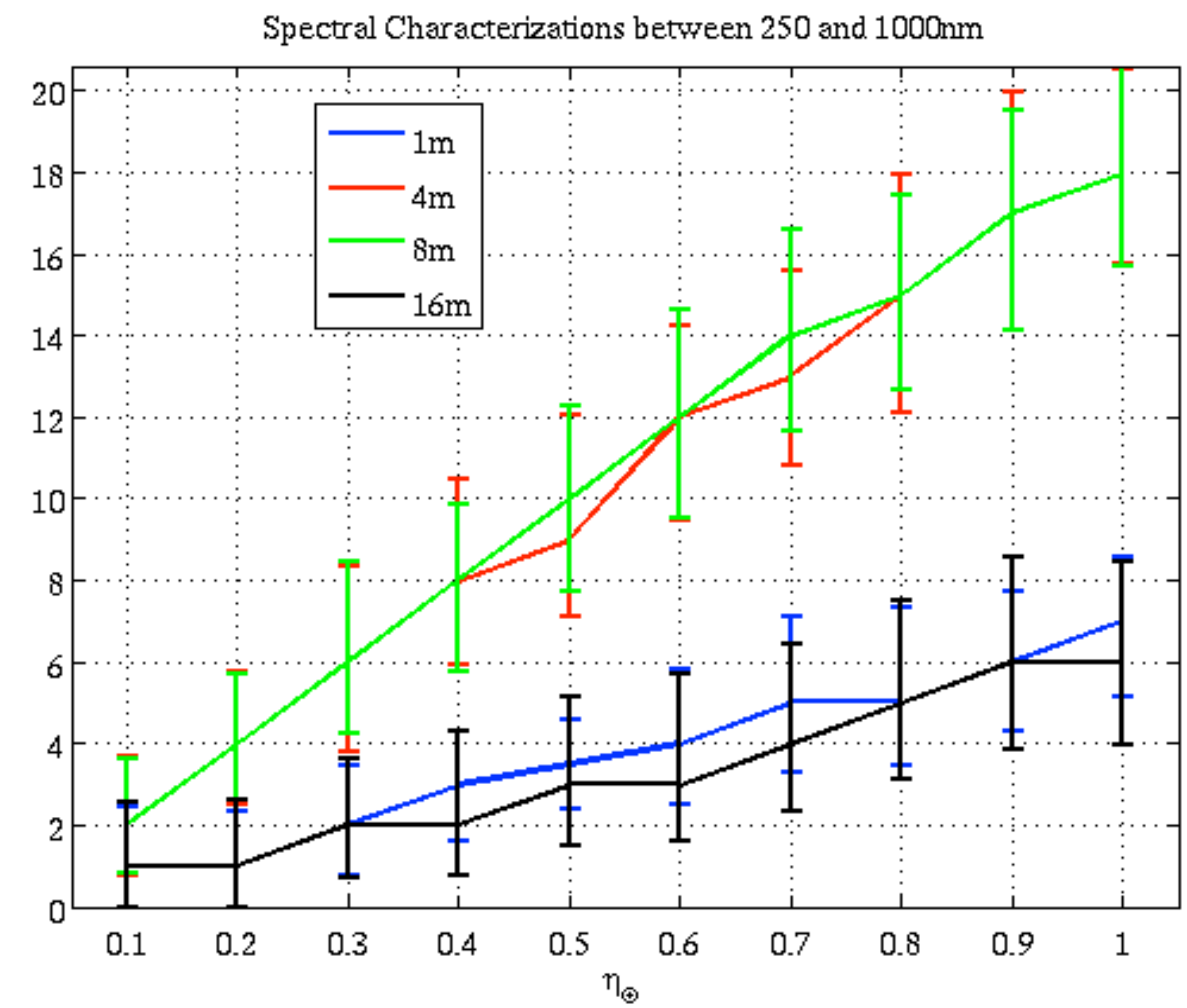
# 8m Telescope




- Over 50 Earth like planets detected at eta = 1
- Same thrusters as 4 m
- 3 lambda/D still IWA limited, but better relative performance than 4 m
- For telescopes ≥ 8 m, coronagraphs outperform occulters

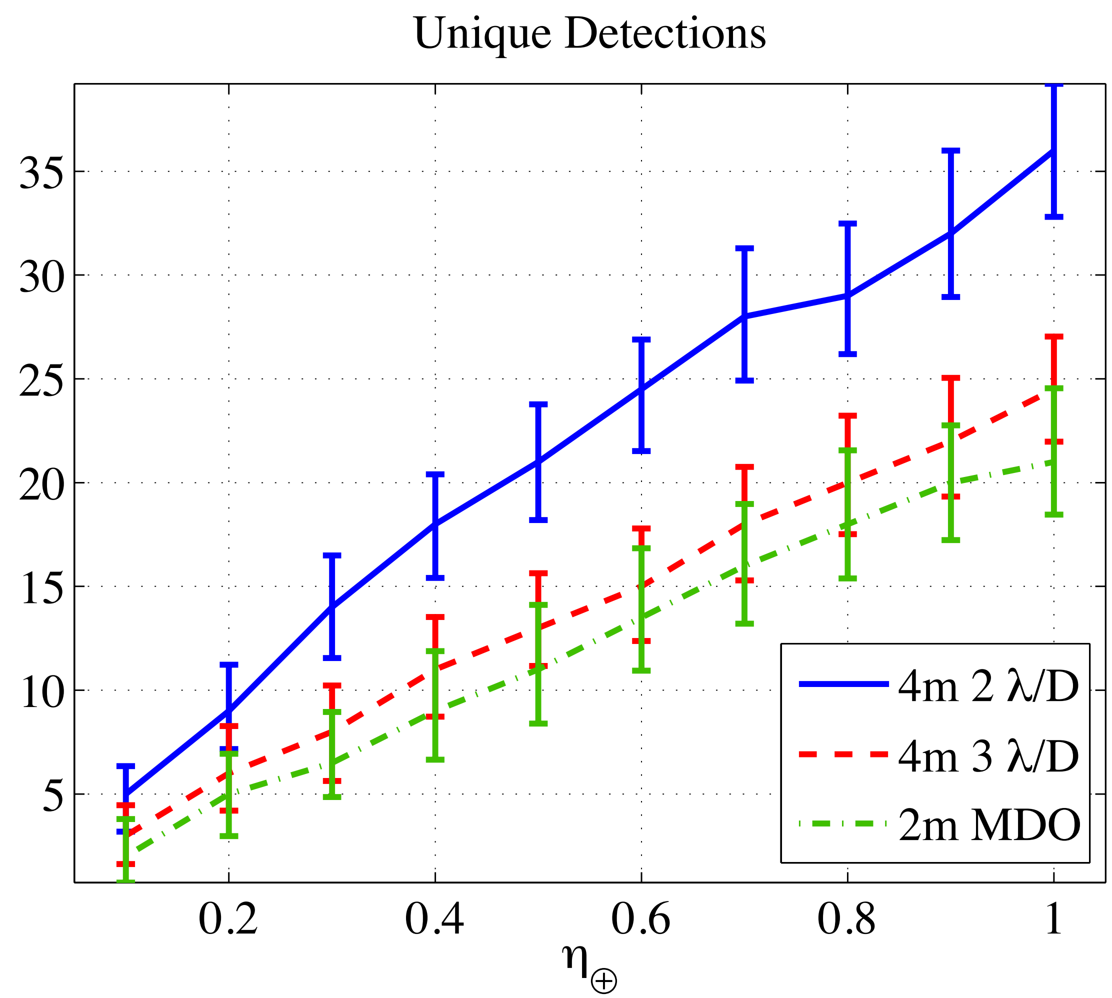
# Multiple Distance Occulters

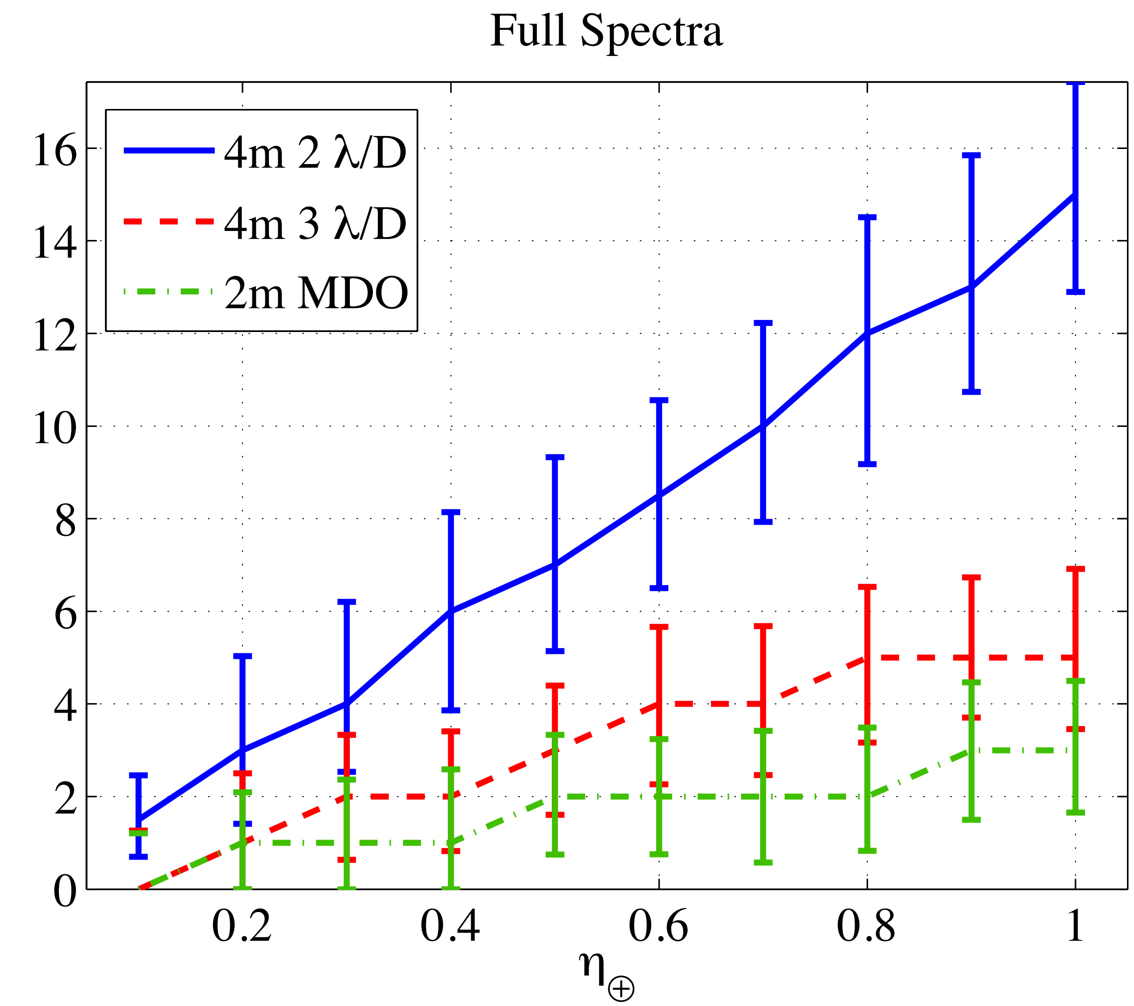



- 4 and 8 m MDO have similar performance
- 16 m MDO has very poor performance compared to coronagraphs
- 1 m MDO does remarkably well (25 Earthlike planets at eta = 1). Only way to get Earths at this scale.

# 2 m MDO compared to 4 m Coronagraphs



# Some Simulation Parameters

Common Elements

- 1, 4, 8, or 16 m circular aperture telescope
- 5 year mission
- 6300kg launch vehicle capacity (or as needed)
- High QE (0.5-0.91), low read noise (3 e/pix) CCDs
- 1000s readouts
- 1.5 exozodi
- 26 limiting delta-mag
- 510000km (azimuthal) Halo orbit
- 250-1000nm spectral capability
- NEXT Ion Thrusters for Occulters
- 50 day single integration time limit

Planet Population

- Earth twins (Earth mass and radius) on habitable zone orbits
  - a in $[0.7,1.5]\sqrt{L}$
  - e in $[0, 0.35]$
  - $p = 0.26$
- $\eta_{\mathrm{Earth}}$ in $[0, 1]$

Requirements

- Maximize visited targets, unique detections and total detections
- For each unique target, acquire one full spectrum, and integrate for S/N = 11 at 760nm with R = 70
- Attempt at least four detections of each discovered planet

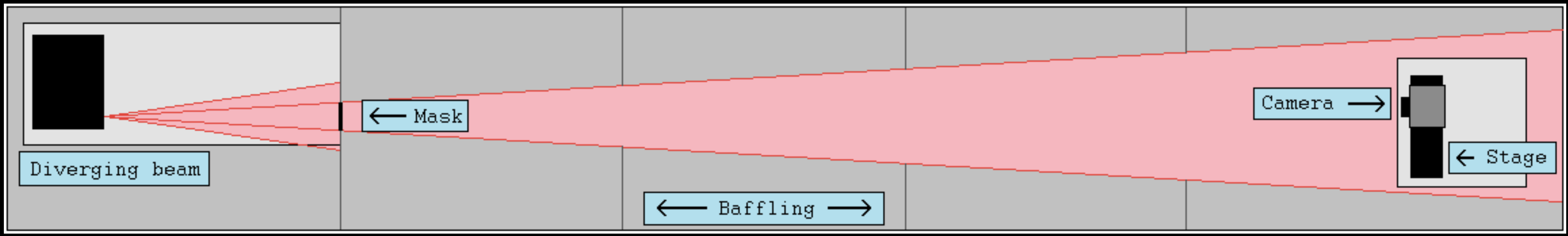
# Mission Designs

- 2 and 3 $\lambda$/D Coronagraphs
  - "Ideal" coronagraph
  - 0.8 maximum throughput
- Single Distance Occulter for 4 m
  - 25.6 m radius (19 m petals)
  - 4200 kg dry mass
  - 70400 km separation
  - 75 mas geometric IWA
  - 59 mas 50% throughput IWA
- Multiple Distance Occulter for 1 & 4 m
  - 20 m radius (10m petals)
  - 3370 kg dry mass
  - 250 - 700 nm at 55000 km separation (75 mas IWA)
  - 700 - 1000 nm at 35000 km separation (118 mas IWA)
  - 57.6 mas 50% throughput IWA
- Single Distance Occulter for 8 m
  - 35.2 m radius (17.6 m petals)
  - 7180 kg dry mass
  - 96800 km separation
- Multiple Distance Occulter for 8 m
  - 27.2 m radius (13.6 m petals)
  - 4915 kg dry mass
  - Separation at 74800/52360 km
- Multiple Distance Occulter for 16 m
  - 43.2 m radius (21.6 m petals)
  - 10022 kg dry mass
  - Separation at 118800/83160 km

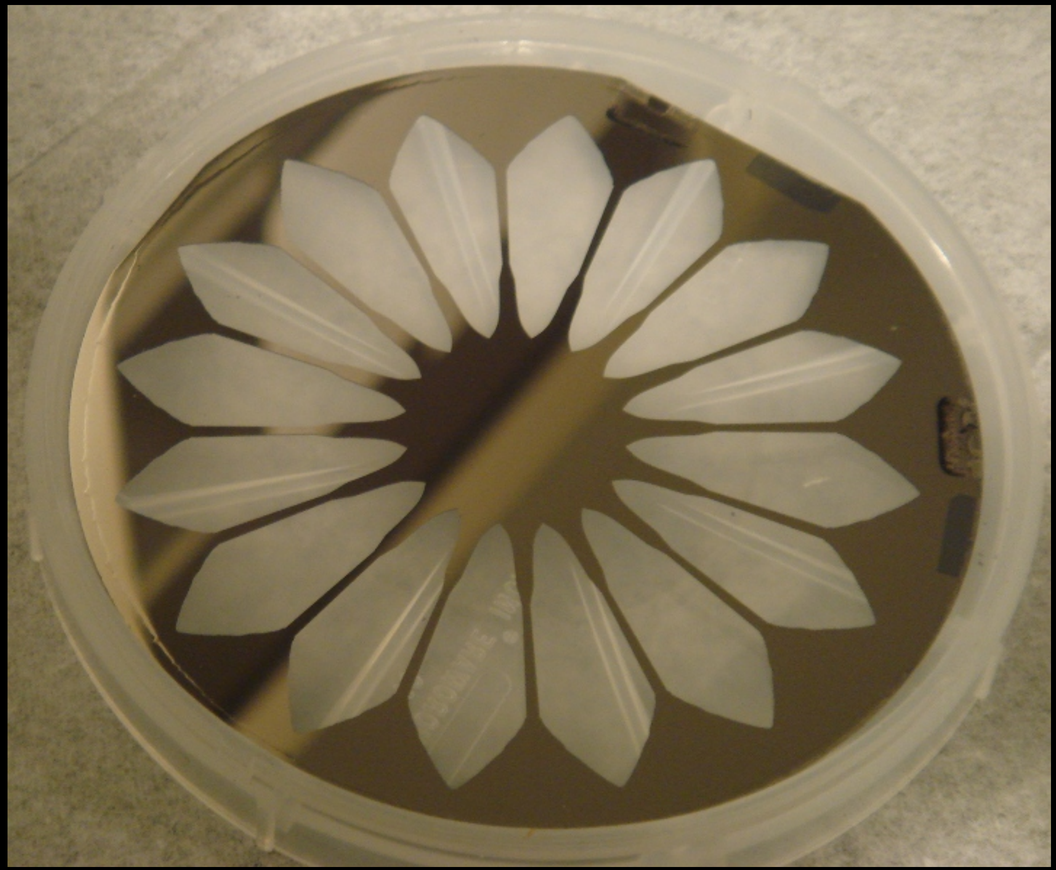
Note: For coronagraphs, 50% of mission for planet finding. For occulters, between 20% and 30%.

# Occulter Experiments

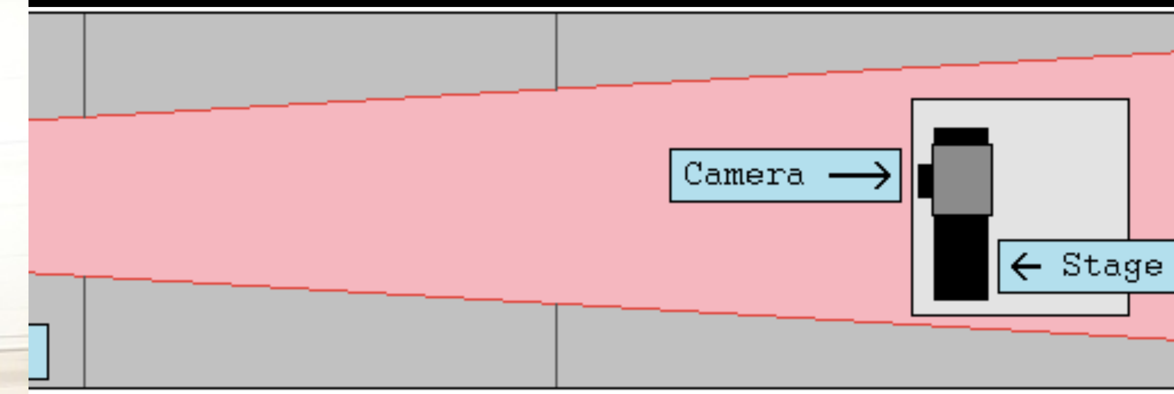
Cady et al. 2010

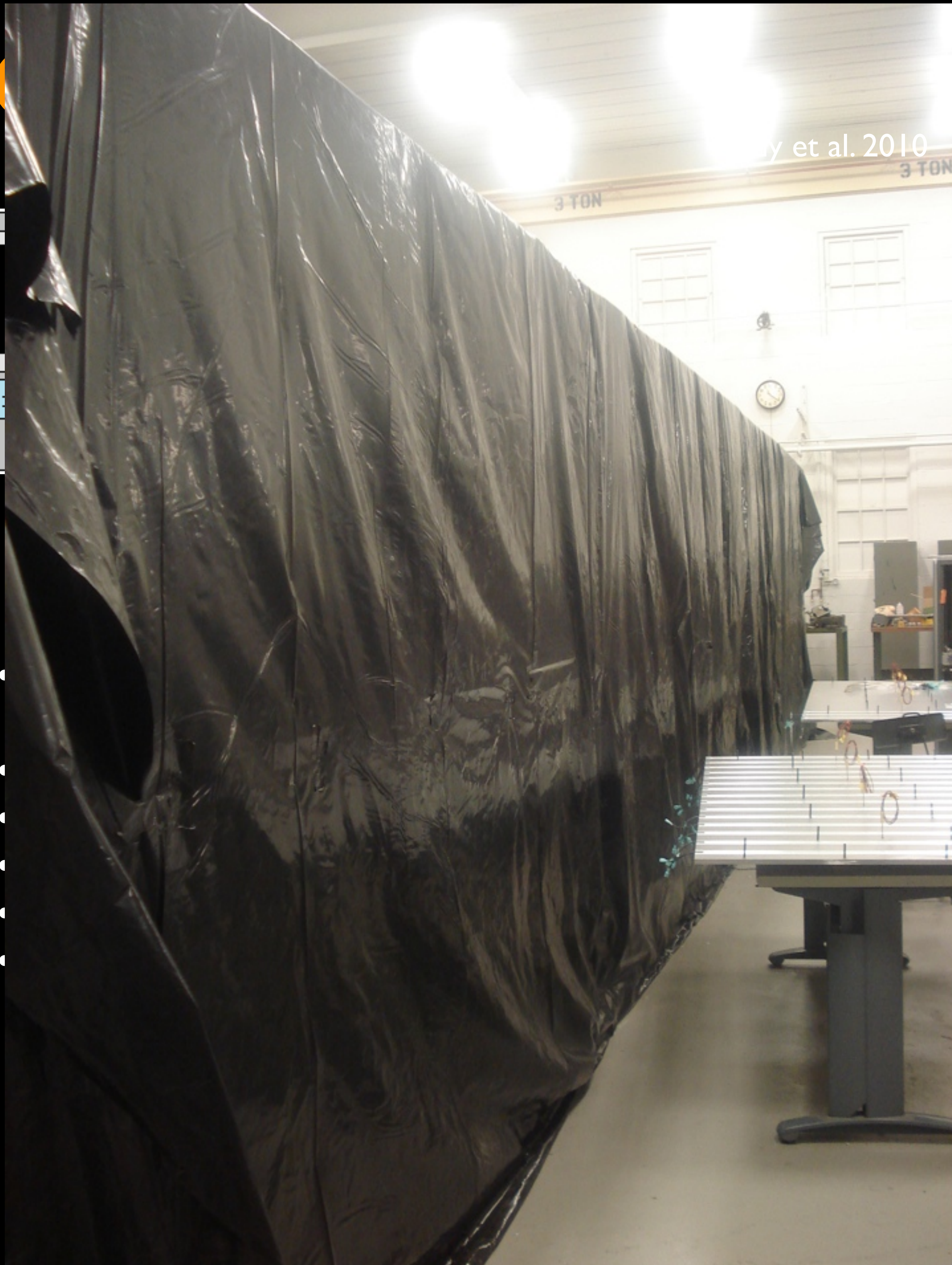


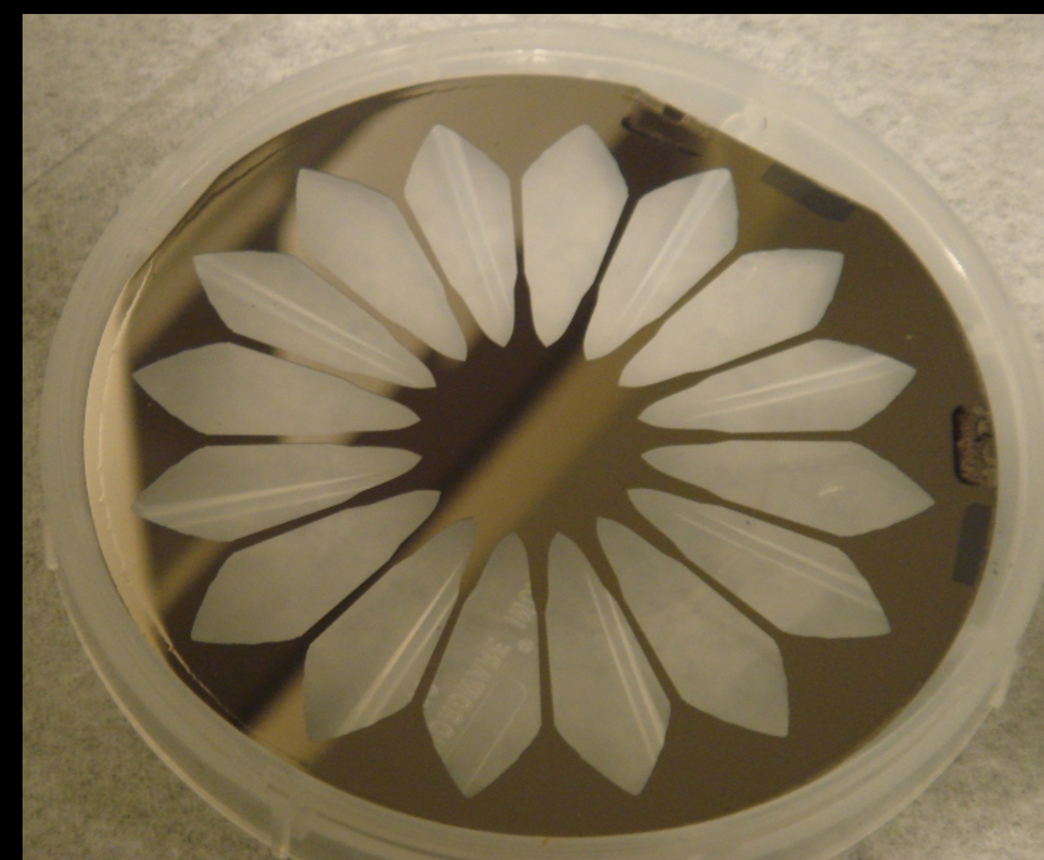

- Inside 40' x 8' x 4' enclosure to isolate from environment
- No optics between pinhole and mask
- No optics (currently) between mask and camera
- 4" diameter, occulter is inner 2"
- Etched from 400m wafer at JPL
- Designed for $10^8$ contrast



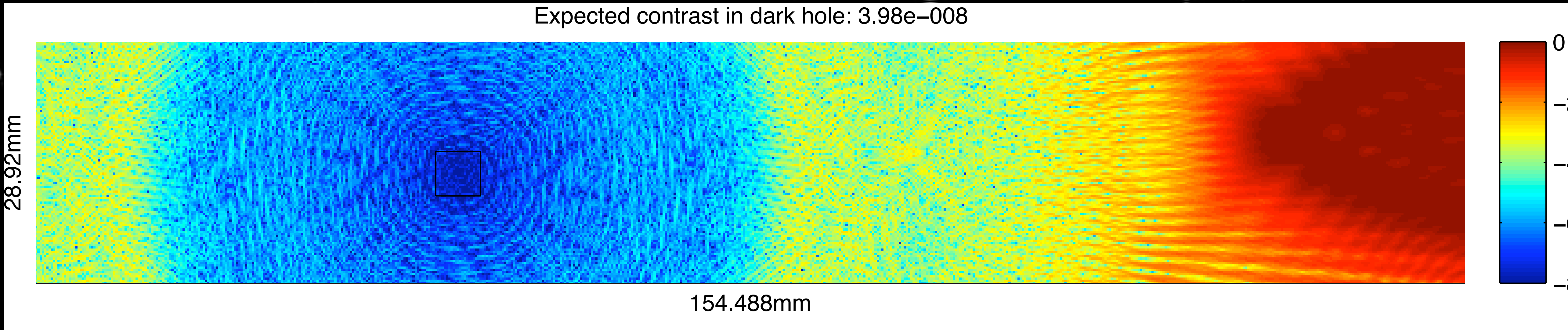
et al. 2010

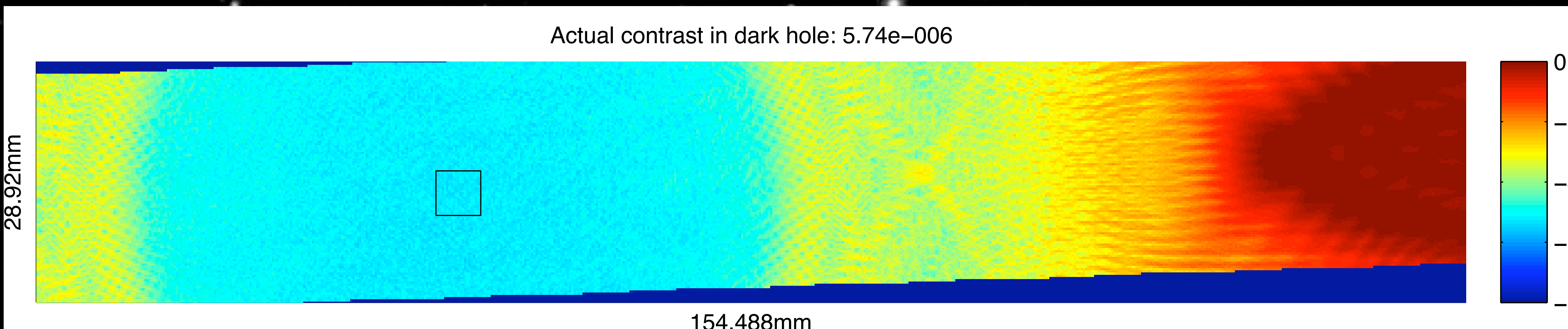


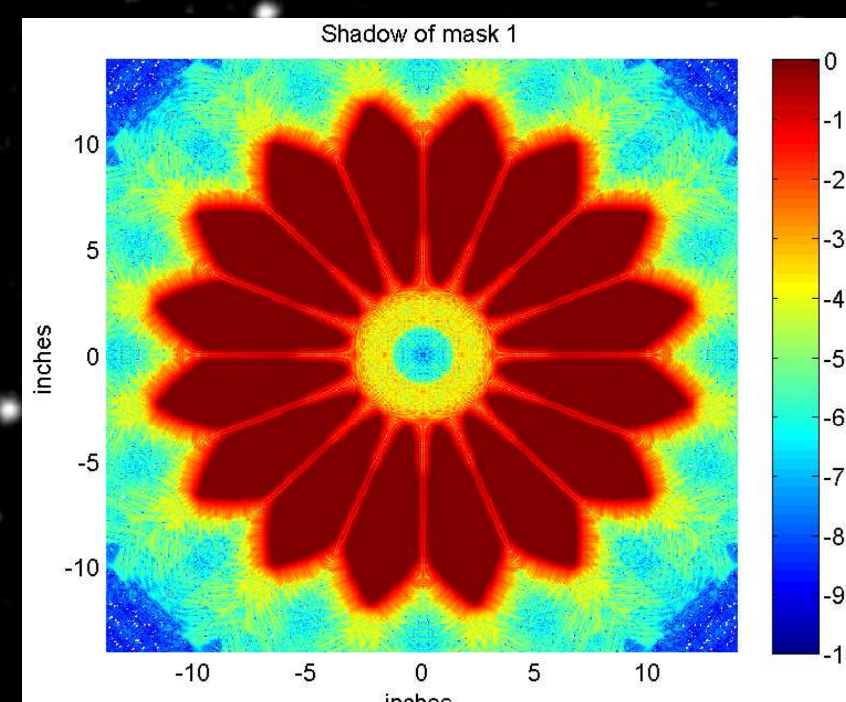





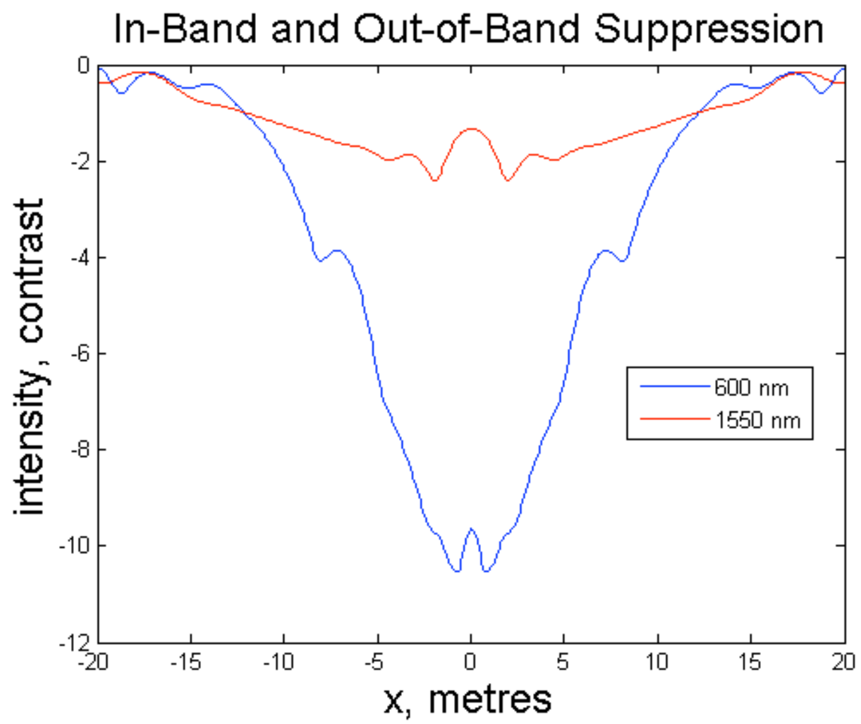
# Experimental Results



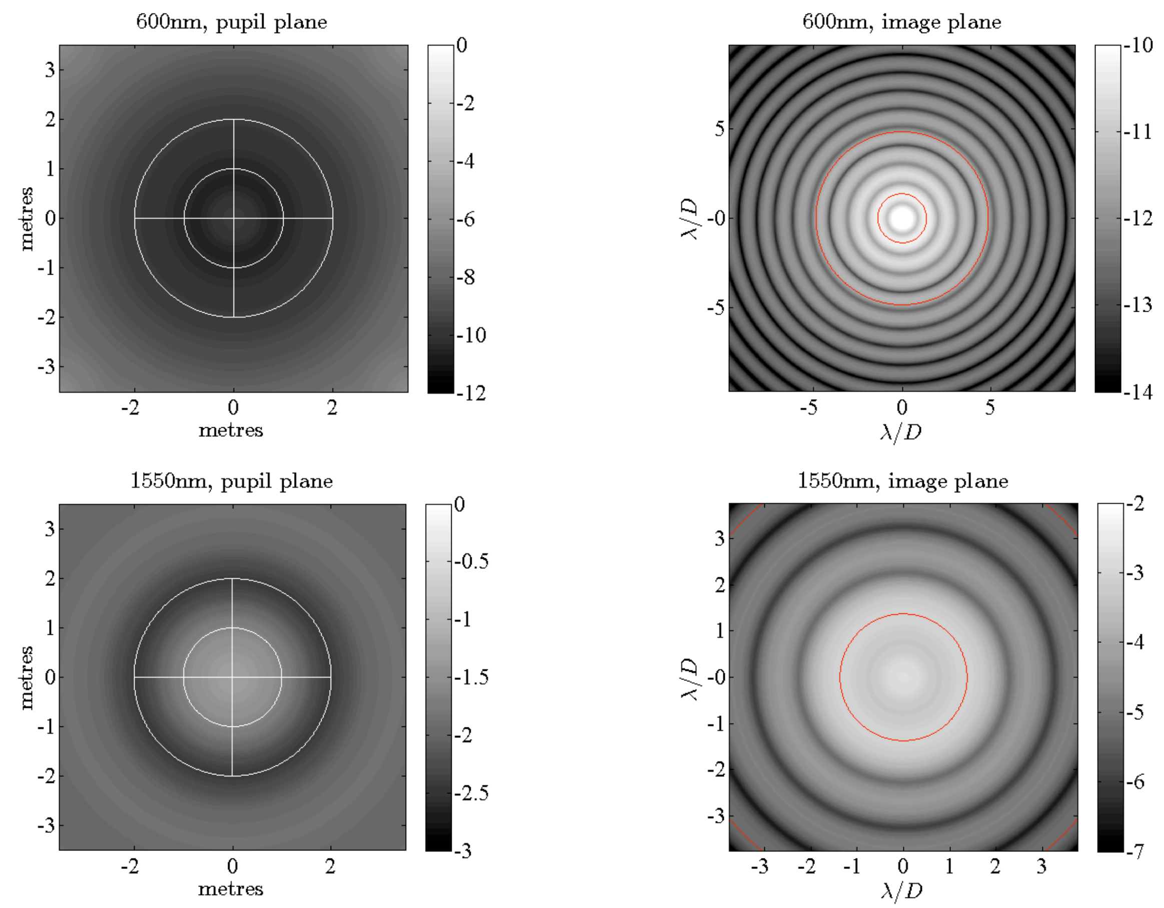



# Position Control (formation flying)

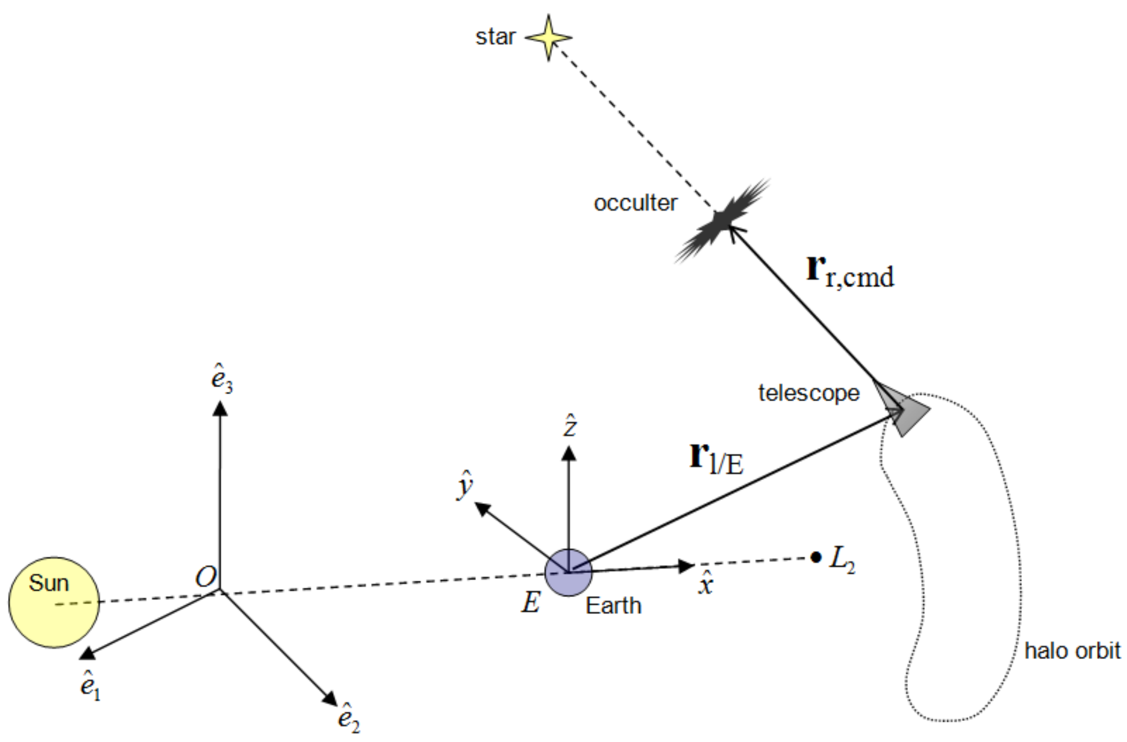



Position sensing using out-of-band stellar leackage

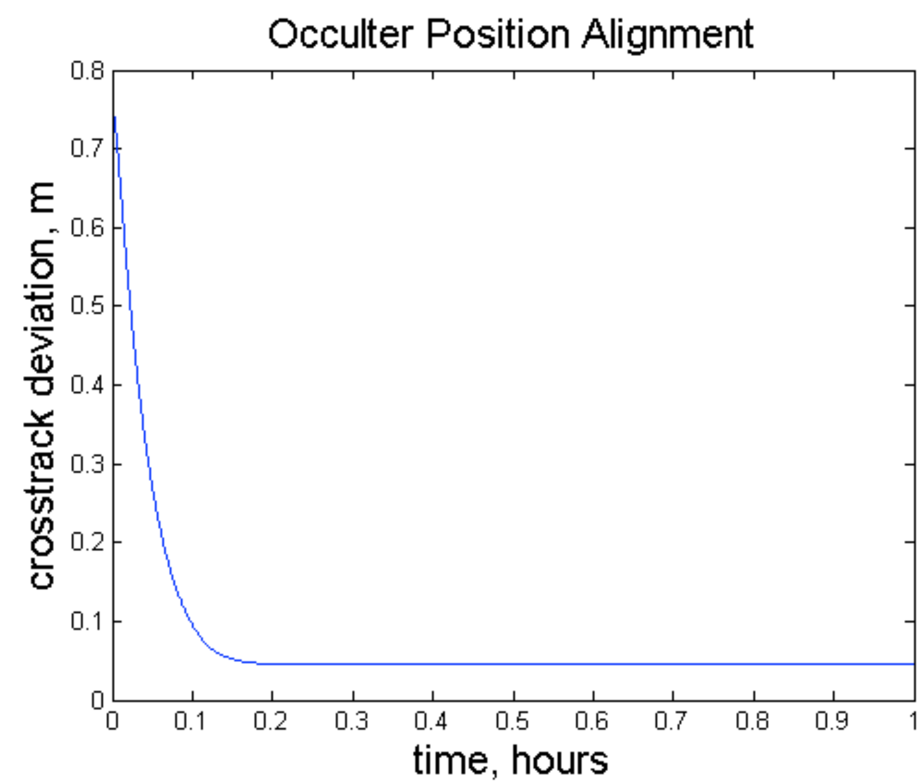



The location of the telescope can be inferred from sampling of the shadow in the pupil plane or via imaging stellar leak

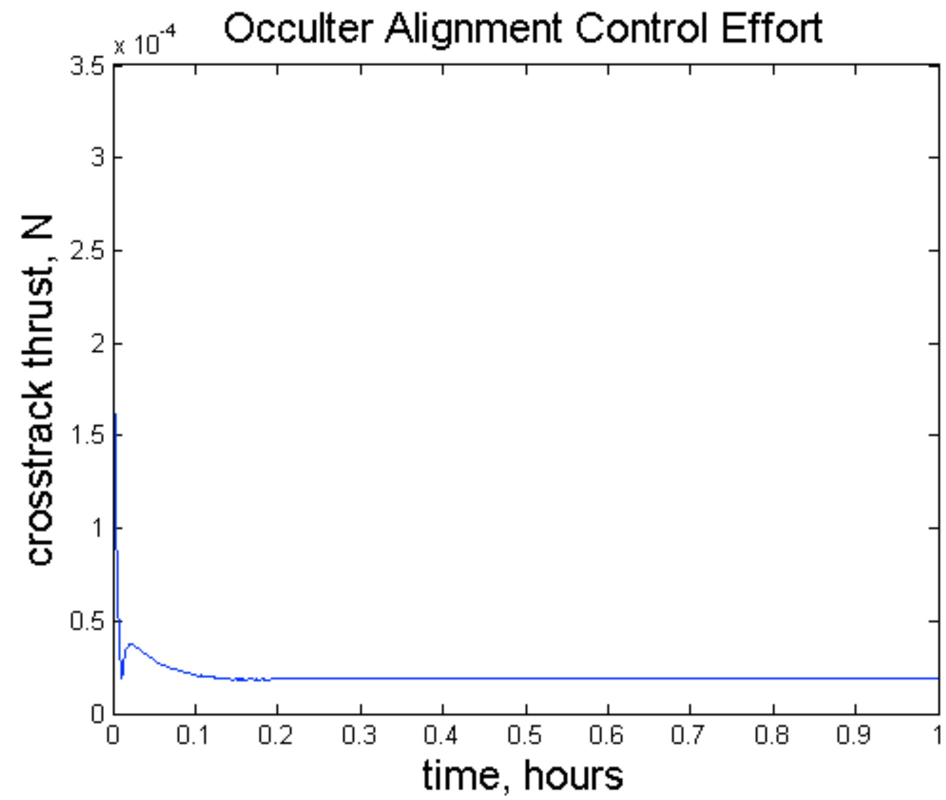
# Position Control (formation flying)



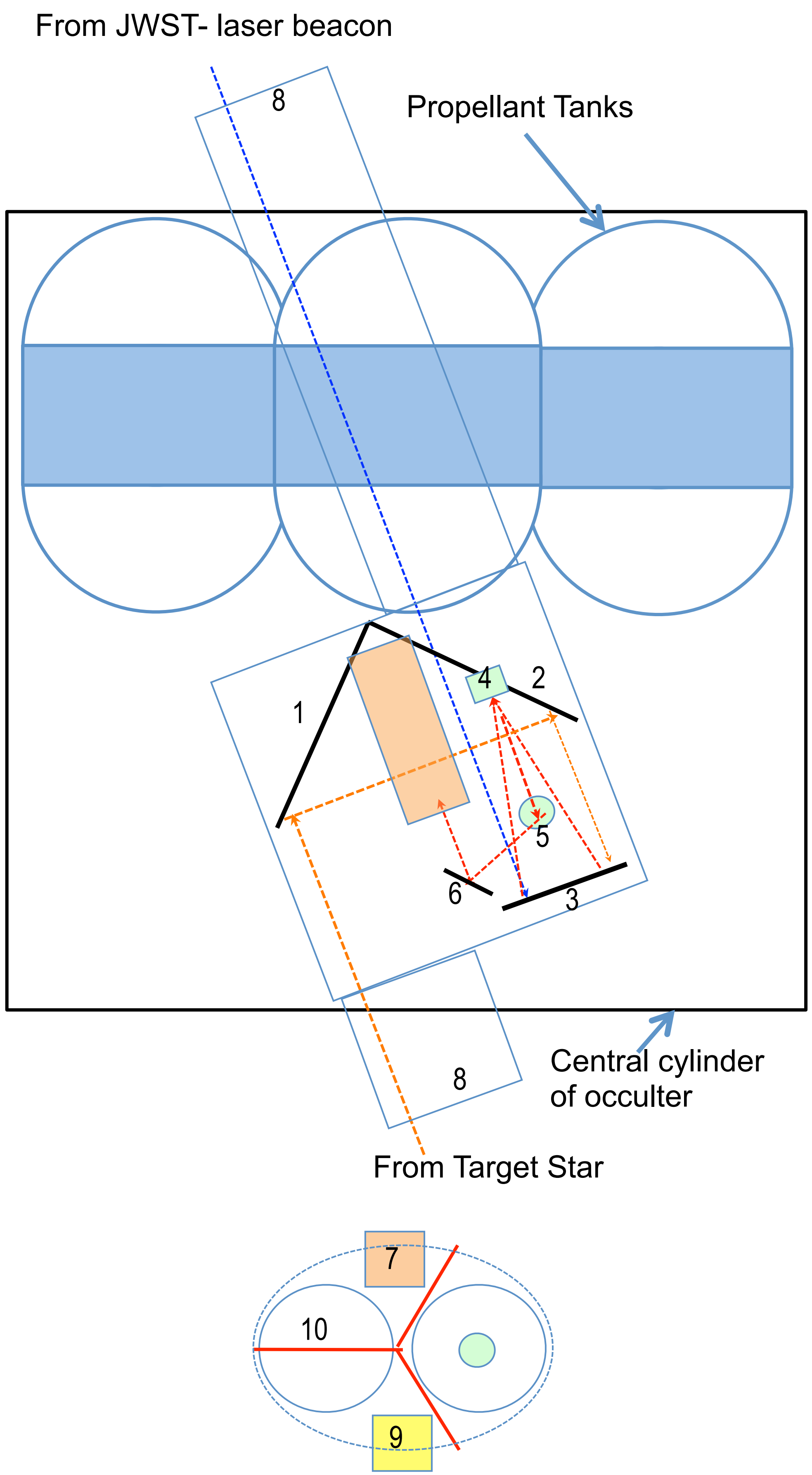

Telescope and Occulter on L2 Halo Orbit




Closed loop control simulation using full dynamic model, pupil position sensing with realistic photon noise (Noecker 2010) and an Extended Kalman Filter and Linear Quadratic Regulator (Sirbu et al. 2010)



# Concept for Sensing JWST Position




- Holding formation requires lateral position sensing to within ~2 mas
- Avoiding large impacts to JWST requires putting a large camera on the occulter and a laser beacon on JWST
- Sensing JWST relative to background stars is not viable
- One option is to combine images of both JWST and the target star onto the same focal plane, as shown to the left
  - ✓ Camera has 2 apertures of ~0.5m diameter, which fit tightly between large propellant tanks (for retargeting maneuvers)
  - ✓ Camera is not alignment critical, except for the dichroic faces relative to each other
  - ✓ Camera is tilted to align with JWST boresight, with occulter tilted relative to JWST (for sun pointing constraints)
  - ✓ Camera design is feasible, but challenging and expensive

**Camera components:**

1. cornrer cube- dichroic face (1)
2. primary mirror
3. secondary mirror
4. fold mirror (bends light out of plane)
5. fold mirror
6. focusing optics & detector
7. light baffles (2 pl)
8. camera electronics
9. corner cube edges (3)